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Space Interferometry Mission

External Review Board

Space Interferometry Mission

SIM

Jet Propulsion Laboratory

March 22 & 23, 2001

A NASA
Origins
Mission

JPL LOCKHEED MARTIN TRW

External Review Board
Welcome & Agenda

Tom Fraschetti
SIM Project Manager

22 & 23 March 2001

SIM Space Interferometry Mission
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AGENDA
March 22, 2001 (Day 1)

01- 8:30	Welcome & Agenda	T. Fraschetti
02- 8:35	Charge to the Board	P. Crane
	Introduction to SIM	
03- 8:45	Science History/Overview	M. Shao
04- 9:45	SIM Technology History	B. Laskin
10:15	Break	
05-10:30	SIM Project Overview	T. Fraschetti
	Mission Concept Overview	
06- 11:00	Interferometry Overview	B. Hines
07- 11:45	Design Study Overview	P. Kahn
12:30	Lunch	
08- 1:15	Science Capabilities of the Different Design Options	M. Shao
09- 1:45	Cost Discussion	J. Marr
10- 2:45	SIM Technology Development	B. Laskin
3:45	Break	
11- 4:00	SIM-SB Design	A. Duncan
12- 5:00	Risk & Reliability Assessment	J. Arnett
5:30	End of Day 1	

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AGENDA

March 23, 2001 (Day 2)

13- 8:30	Discovery and Characterization of Other Solar Systems	S. Kulkarni
14- 9:00	The SIM Planet Program	G. Marcy
14.5	ERB Question, Planets Everywhere	M. Shao
15- 9:30	Wide Angle Astrometry	S. Unwin
10:00	Break	
	Wide Angle Astrometry Science Talks	
16- 10:15	Stars	T. Henry
17- 10:35	Galactic	A. Gould
18- 10:55	Extra-Galactic	A. Wehrle
19- 11:15	Science Summary	C. Beichman
20- 11:45	Project Summary	T. Fraschetti
12:00	Lunch	
1:00	Board Deliberations	
5:00	End of Day 2	

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Five Key Questions

1. Does SIM fit in the larger framework of other missions and other techniques? ***YES***
   - SIM does unique science that no other planned mission can/will do
   - TPF needs SIM (technology, target identification, planet masses)
2. Is SIM feasible from an engineering and technology perspective? ***YES***
   - SIM new design is much less complex and risky than the Reference Design, and is now no more complex than missions that have successfully flown (per the SIMTAC)
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap? ***YES***
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets? ***NO***
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry? ***YES***
   - This capability allows SIM to detect long-period (>5 year) planets necessary for TPF
   - Global Astrometry is a key science capability endorsed by the Decadal Reports

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SIM External Review Board Meeting

Philippe Crane
SIM Program Scientist
NASA Headquarters
22 March 2001

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CHARTER

- The SIM External Review Board will review the proposed capabilities of the SIM architectures to evaluate:
  - the extent to which the expected scientific performance of these architectures conforms to those foreseen in the NRC Decadal reports,
  - the extent to which SIM will detect planets in the habitable zone in support of the TPF mission,
  - the extent to which the scientific return of the various proposed implementation of the SIM mission are commensurate with the cost differentials, and
  - the extent to which the implementation approach is sufficiently mature to guarantee the science goals will be met.

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Role of the Space Interferometry Mission in the Origins Theme

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- Key Origins Goal is to find and study Earth-like planets
- Terrestial Planet Finder(TPF) is the cornerstone mission which is still to be defined.
- SIM is on the critical path for TPF in two major ways
  - SIM can provide the knowledge base we need in order to know which stars actually have earth like planets in the habitable zone.
  - SIM will provide a critical technical base for TPF no matter what design is chosen for TPF (Interferometer or corona-graph)
- SIM must justify itself to NASA HQ on these grounds not as an astronomy mission because
- OMB and Congress have been told that SIM is necessary for TPF.

Schedule of Events

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- Known Events
  - March 26 Presentation to Anne Kinney (PC, LP, RH)
  - March 28 Presentation to Ed Wieler (AK,PC, LP, EJW,RH)
  - May 15 SIM Replan meeting with IA and ERB
- Presumed Event
  - Early April Wieler/Kinney discussion with OMB
  - Early April Wieler/Kinney discussion with Goldin

Charge to the ERB

- RISK vs Performance: How can we reduce risk without compromising performance??
- Is a "Planets mostly" mission acceptable?
- What is a minimum mission?
- What is the most likely failure mode? And what are the consequences??
- Is the testing process adequate?
- If NASA offered $100,000 as a prize to improve the probability of success, what would you suggest?
- Are there other ways to find the actual targets for TPF? I.e. KEPLER or ECLIPSE or ??

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Charge to the External Review Board

- Listen Attentively
- Question Deeply
- Recommend Wisely

Even if SIM meets all the requirements that HQ has set, there is no guarantee that it will survive. OMB and Dan Goldin are very aware the $930M is not $550M and that $930M is a VERY big number.

WE MUST BE VERY CONVINCING!

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Science History, Overview of SIM Space Interferometry Mission

M. Shao

Project Scientist

SIM Science Team

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Key Science Projects

Names	Institutions	Topic
Dr, Geoffrey Marcy	University of California, Berkeley	Planetary Systems
Dr. Michael Shao	NASA/JPL	Extrasolar Planets
Dr. Charles Beichman	NASA/JPL	Young Planetary Systems and Stars
Dr. Andrew Gould	Ohio State University	Astrometric Micro-Lensing
Dr. Edward Shaya	Raytheon ITSS Corporation	Dynamic Observations of Galaxies
Dr. Kenneth Johnston	U.S. Naval Observatory	Reference Frame-Tie Objects
Dr. Brian Chaboyer	Dartmouth College	Population II Distances & Globular Clusters Ages
Dr. Todd Henry	Georgia State University	Stellar Mass-Luminosity Relation
Dr. Steven Majewski	University of Virginia	Measuring the Milky Way
Dr. Ann Wehrle	NASA/JPL	Active Galactic Nuclei

Mission Scientists

Dr. Guy Worthey	St. Ambrose College	Education & Public Outreach Scientist
Dr. Andreas Quirrenbach	University of California, San Diego	Data Scientist
Dr. Stuart Shaklan	JPL	Instrument Scientist
Dr. Shrinivas Kulkarni	California Institute of Technology	Interdisciplinary Scientist
Dr. Ronald Allen	Space Telescope Science Institute	Imaging and Nulling Scientist

Outline

- History of SIM
  - Heritage from ground based interferometers
  - 1990 decadal report
  - 2000 decadal report
- SIM and planets, comparison with other missions
- SIM as a necessary step towards TPF
  - Technology precursor, Target selection, Planetary systems
- SIMSWG and an overview of SIM science
- Summary

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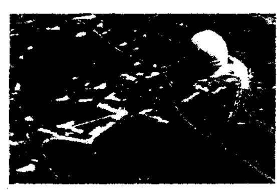
Historical Note

- The basic idea for SIM is a Michelson Stellar Interferometer
- A series of interferometers from the Mark III on Mt Wilson, to the Palomar Testbed Interferometer, and the Keck Interferometer provide the technical and scientific foundation upon which SIM is being designed.
- In 1990, the Bahcall Report "Decade of Discovery" recommended that NASA undertake an astrometric Interferometer Mission. SIM is that mission.
- This commitment was renewed in the 2000 decadal report "Astronomy and Astrophysics int the New Millenium".



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Ground Based Precursors to SIM

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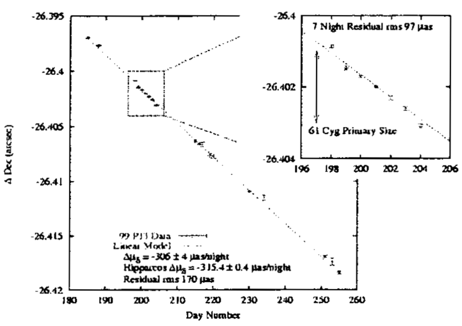
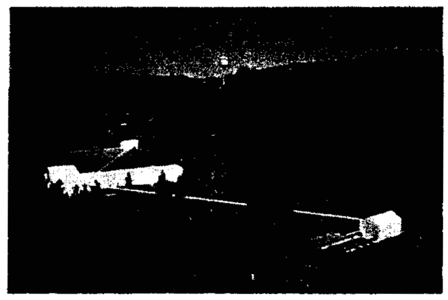
- Astrometry, Palomar Testbed ~ 100uas





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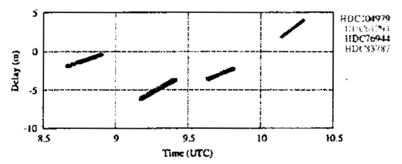

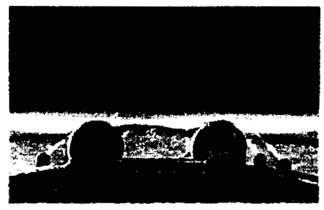

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Astrometric Planet Detection

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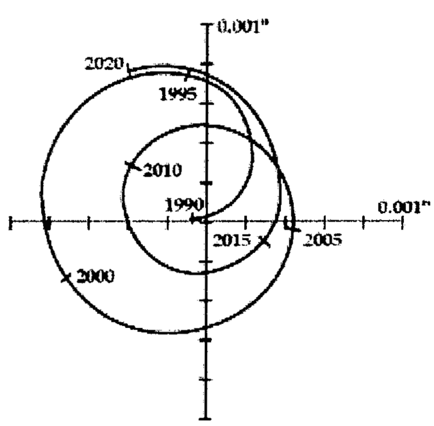
- Astrometry looks for the transverse motion of a star caused by orbiting companion(s)
- Because astrometry measures the motions in two directions, there is no (sin i) ambiguity
- Astrometry is more sensitive to "outer" planets
- Size of effect at 10pc
  - Sun-Jupiter 0.5 mas
  - Sun-Neptune (12 yr) 15 uas
  - Sun-Earth (1yr) 0.3 uas



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Astrometric Planet Detection
What's Measured?

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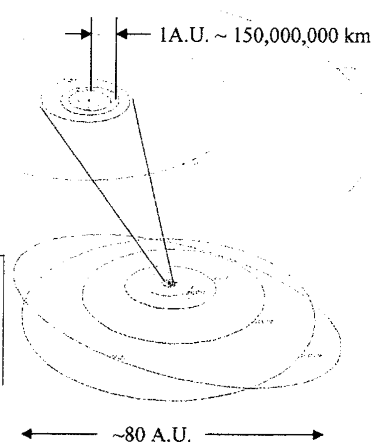

Astrometry can measure all of the orbital parameters of all planets.

Orbit parameter	Planet Property
Mass	atmosphere?
Semimajor axis	temperature
Eccentricity	variation of temp
Orbit Inclination	Coplanar planets?
Period	

Sun's reflex motion (Jupiter) ~500 uas
Sun's motion from the Earth ~0.3 uas

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Astrometric Planet Detection

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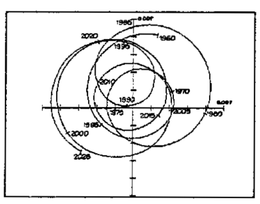

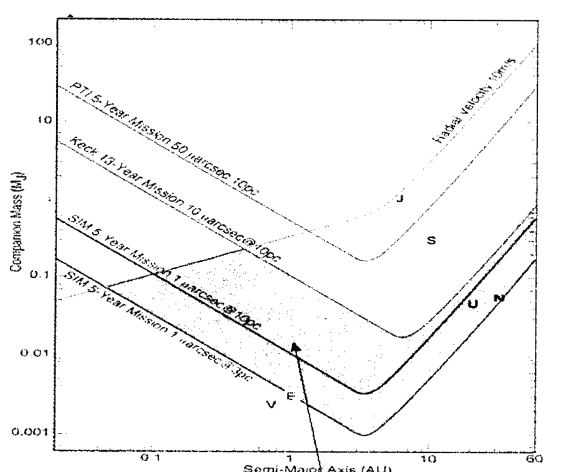

Systems only accessible with SIM

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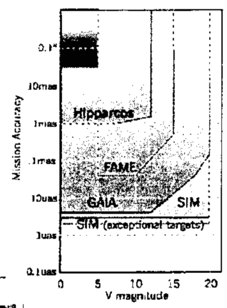
Detection Limits
SIM: 1 µas over 5 years (mission lifetime)
Keck Interferometer: 20 µas over 10 years

Planet Detection Comparison



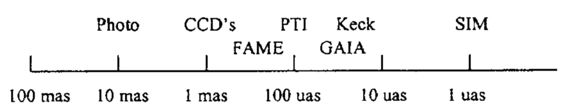
Global Astrometry comparison does not illustrative the true difference between SIM and other Space Astrometry Missions

Many other astrometry missions are scanning spacecraft. SIM is a pointed spacecraft and in the area of planet detection SIM is orders of magnitude more sensitive than other planned future astrometry missions

SIM Planet detection program ~ 50 measurements (x,y) over a 5 yr period (10yrs if extended mission is approved) single measurement accuracy ~ 1uas, equivalent mission accuracy is ~0.15 uas.

FAME mission accuracy ~36 uas, equal to 50 measurements each accurate to **~ 260 uas**.

GAIA mission accuracy is 4 uas, equal to 50 measurements each accurate to **~28 uas**, (vs **1uas** for SIM)



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SIM is a Precursor to TPF (Technology)

- SIM provides technology necessary for TPF
  - Demonstrates interferometry in space
  - Laboratory demonstration of nulling
  - Laboratory demonstration of optical path control at nanometer level in a large flexible structure
- TPF in order to detect the light from an Earthlike planet will need both high spatial resolution and large collecting area. (vis or IR)
  - At any wavelength, TPF will have a very demanding high contrast imaging problem that will require sub nanometer optical path stability
  - SIM provides the technology for stabilizing optical paths of a large flexible structure in space at ~1 nanometer levels
  - SIM provides the technology for measuring optical paths and wavefronts at the subnanometer level. (in space)

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Sub-Nanometer Control for TPF

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- The baseline design for TPF is an IR nulling interferometer
  - Null to 1e-6 needs optical path **control** to **800 picometers (pm)**
- The Eclipse mission (proposed Discovery Mission) is a ~2m telescope/coronagraph
  - Direct detection of Jupiters (visible)
    - 0.5 arcsec from star
    - 10^9 fainter than star
    - Needs 1 angstrom (100 pm) wavefront
  - Direct detection of Earths is more difficult
    - 0.1 arcsec from star
    - 10^{10} fainter than star
    - ~10m telescope, same wavefront accuracy for a ~10m dia telescope

Wavefront accuracy to 100pm implies that vibrations are **controlled to 100pm**

- SIM needs to **control** optical path difference (OPD) to **10nm** for astrometry
- In the past, SIM had a technology requirement to **control** OPD to **800 pm** as part of a nulling technology demonstration for TPF.
- Nulling has two major technological components
  - The nulling beam combiner
  - **Extreme (IR)** or **Ultra Exterme (Vis)** Vibration control of a large flexible structure or surface
- To save money the SIM project has eliminated the nulling combiner in space. Vibration suppression is a goal not a requirement.

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Nulling Interferometers

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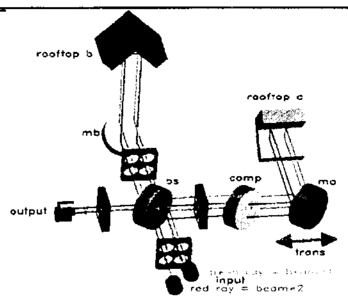
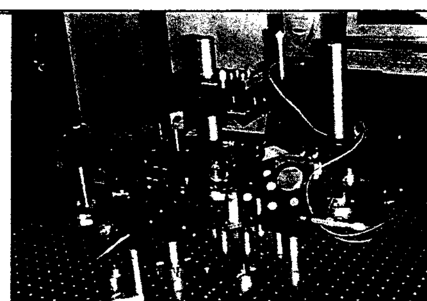
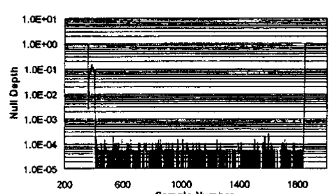
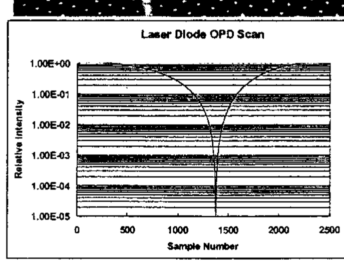






Continuous Null > 10,000:1



Transient null > 100,000:1

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TPF Targets

- TPF will have sufficient sensitivity to measure a low resolution spectra of an Earthlike planet's emission out to ~ 10 parsec.
  - SIM will search virtually every single star out to 10pc for Terrestrial planets with in the habitable zone down to 3 Earth Masses. (1 uas **Deep Search**)
- TPF will have the sensitivity to detect the light from an Earthlike planet out to ~ 20pc.
  - SIM will search virtually every single star out to 20pc (4 uas **Broad Survey**)
  - SIM will find planetary systems like our own (Jovian planets in Jovian orbits) as potential targets for TPF. But perhaps more important SIM with its large number stars in the broad survey, will place our solar system and its planet in the context of planetary systems in this part of the galaxy.
- Understanding planetary systems is key to a search for Earthlike planets
  - Are Jupiters at 0.1 ~ 1 AU the rule or the exception to the rule? Are Jupiters at 5 AU, the norm or a rare event? Are multiple planetary systems always in co-planar orbits, or rarely in coplanar orbits?
  - Are planetary system like ours common in the galaxy?
  - Are terrestrial planets common?
  - Where are the terrestrial planets?

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SIM Science Summary
SIM Planet Science

- The SIM planet science program has 3 components.
- Achieves the goal of searching ~250 nearby stars for terrestrial planets, in its **Deep Search** at (1 uas).
- Achieves the goal of searching ~ 2000 stars in a **Broad Survey** at lower but still extremely high accuracy (4uas) to study planetary systems throughout this part of the galaxy.
- Achieves the goal of studying the birth of planetary systems around **Young Stars** so we can understand how planetary systems evolve.
  - Do multiple Jupiters form and only a few or none survive during the birth of a star/planetary system?
  - Is orbital migration caused primarily by Planet-Planet interaction or by Disk-planet interaction?

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SIM Preserves General Astrophysics Goals

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- Two NAS decadal reviews have endorsed the fundamental astrophysics enabled by wide-angle astrometry
  - Only SIM can observe objects as faint as 20 mag with astrometric accuracy of 4 μas
- Astronomy typically advances most successfully with a combination of pointed and survey observations
  - Detailed pointed observations of ~10^4 objects of particular interest with SIM will complement the astrometric survey planned with the FAME mission
- SIM will be 10-100 times more accurate than FAME, depending on magnitude, and will observe faint objects that FAME cannot observe at all (V>15 mag)

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The Distance Scale and Stellar Evolution

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- Distances to galactic cepheids to a Kpc can be measured to <1% accuracy, a key element in the cosmic distance scale
- The utility of RR Lyrae stars as a distance indicator depends on knowing their properties as a function of metallicity
  - Only SIM can observe RR Lyrae stars in globular clusters spanning -2.0 < [Fe/H] < -0.7
- SIM will permit 1% mass measurements over the whole range of stellar types, including
  - Black holes, OB stars to brown dwarfs, and white dwarfs.
  - In addition, by obtaining precision masses for stars in clusters covering a range of ages (1 Myr -- 5 Gyr) and a variety of metallicities, SIM will directly probe stellar evolution as a function of age as well as mass.

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Dynamics of Galaxies

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- SIM will investigate the dynamics of the Milky Way
  - Determine 3-D gravitational potential of Milky Way via precise distances to stars, globular clusters and satellite galaxies to ~100 kpc
  - Determine precise phase-space coordinates of the Sun relative to the Milky Way to anchor FAME and GAIA catalogs
- SIM will investigate galaxy dynamics based on true orbit determinations
  - SIM will measure proper motions of 30 Local Group and other nearby galaxies (50 μas/yr) from observations of individual V=16 ~ 20 mag stars
  - Results will include dark matter distribution, merger history, mutual influence of groups

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Active Galaxies and Fundamental Physics

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- SIM astrometry at different colors will distinguish between various jet and disk models of AGN
  - SIM can detect the orbital motions of two merging AGN (OJ287?)
- SIM will use astrometry and photometry of micro-lensing events to determine physical properties of lensing stars
- SIM can test Mach's Principle to 5% accuracy
  - By comparing SIM (ecliptic inertial frame) and radio (QSO rest frame) positions of the white-dwarf/pulsar binary, PSR J1012+5307, SIM will test the linkage between these different reference frames

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Science Summary

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- SIM plays a critical role in the Origins theme, leading to TPF
  - Develop many technologies critical to a range of future NASA science missions.
  - As a science precursor to TPF, SIM will place terrestrial planets and our solar system in the context of planetary systems in our part of the galaxy, in addition to providing a target list for TPF.
- SIM's global astrometry capability will result in major advances across a broad area of astrophysics. Endorsed by two decadal survey reports, SIM will leave a rich science legacy.

Five Key Questions

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External Review Board Technology History

Bob Laskin
SIM Project Technologist

22 & 23 March 2001

Outline

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- The SIM technology challenge
- Brief history of technology development

How Does SIM Do Astrometry?

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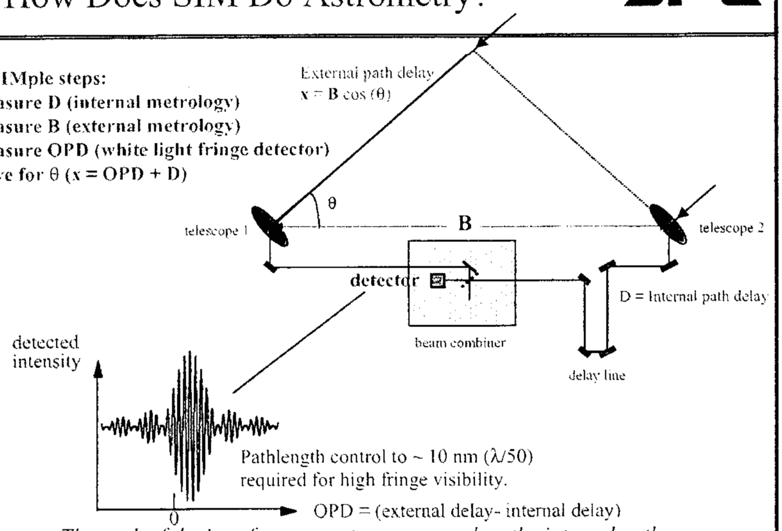
Four SIMple steps:

1. **Measure D (internal metrology)**
2. **Measure B (external metrology)**
3. **Measure OPD (white light fringe detector)**
4. **Solve for θ (x = OPD + D)**



- *The peak of the interference pattern occurs when the internal path delay equals the external path delay*

SIM Technology Challenges

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- Picometer knowledge (100 pm = diameter of a hydrogen atom)
  - Picometer laser metrology
  - Picometer starlight fringe position measurement
  - Data post-processed on ground to achieve astrometry science
- Nanometer control (75,000 nm = thickness of a human hair)
  - Needed for high SNR fringe => picometer fringe measurement
- Millikelvin thermal stability of optics
- Overall instrument complexity
  - Autonomous operation
  - Instrument modeling, integration and test

Key SIM Technologies

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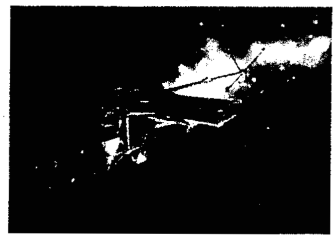
Picometer Technologies

Nanometer Technologies

Interferometer Modeling
Integrated Optical, Mechanical, Thermal & Control

Metrology
Sub-Nanometer Relative Knowledge

Quiet Structures
Micron Stability



Starlight Fringe Detection
Sub-Nanometer Fringe Tracking

Active Optics
Nanometer Control

Thermally-Stable Optics
Milli-Kelvin Thermal Stability

Interferometer I&T

Control-Structure Interaction (CSI) Program

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- Formed by NASA Code R in late FY'88
  - Rose from ashes of LaRC COFS (Control of Flexible Structure) Program
  - Multi-center program funded at ~ $15M/yr level
    - LaRC -- focus on Mission to Planet Earth missions
    - JPL -- focus on large optical space systems
    - MSFC -- responsible for major CSI flight experiments
- JPL chose space optical interferometry as technology driver
  - Funded at ~ $2.5M/yr level
  - Developed a Focus Mission Interferometer (FMI)
  - Developed Integrated Modeling of Advanced Optical Systems (IMOS)
  - Built three increasingly sophisticated vibration attenuation testbeds
  - Developed ties to the space interferometry science community (SISWG)
  - Prevented by charter from working on laser metrology

Key CSI Technologies

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Nanometer Technologies

Interferometer Modeling
Integrated Optical, Mechanical, Thermal & Control

Quiet Structures
Micron Stability

Active Optics
Nanometer Control

Interferometer I&T

CSI Focus Mission Interferometer

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- The FMI was used to drive all aspects of the technology development
  - Modeling tools
  - Analytical methods
  - Component hardware development
  - Testbeds
  - Flight experiments

Integrated Modeling -- IMOS

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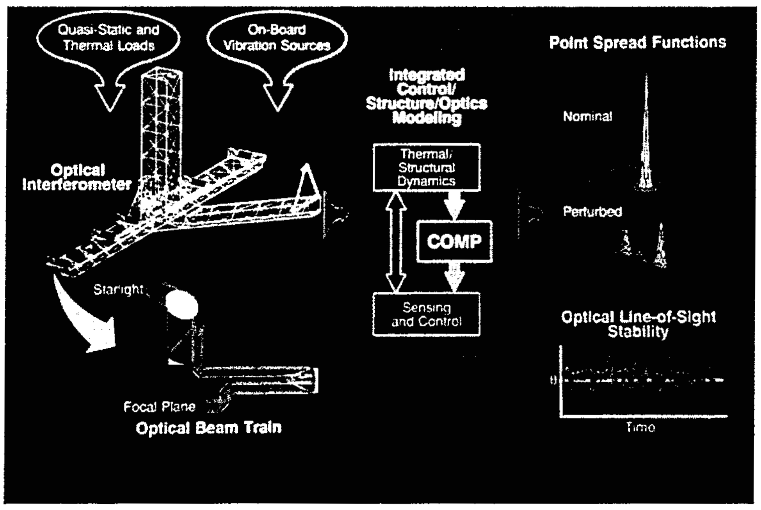

Multi-Layer Design for the FMI

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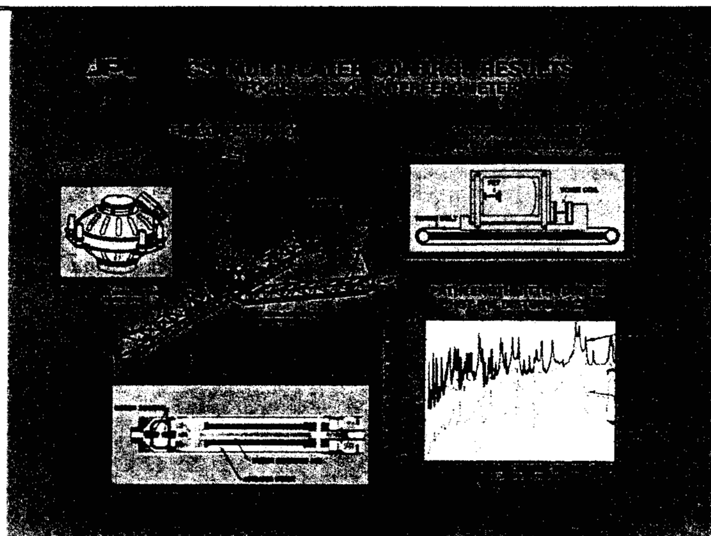

CSI Phase B Multi-layer Testbed

SIM Space Interferometry Mission

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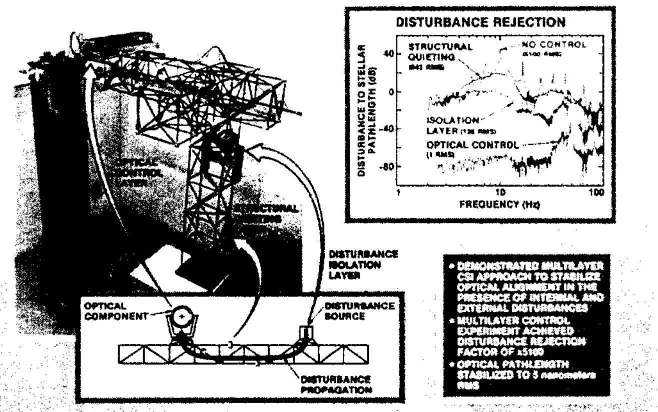

Micro-Precision Interferometer (MPI)

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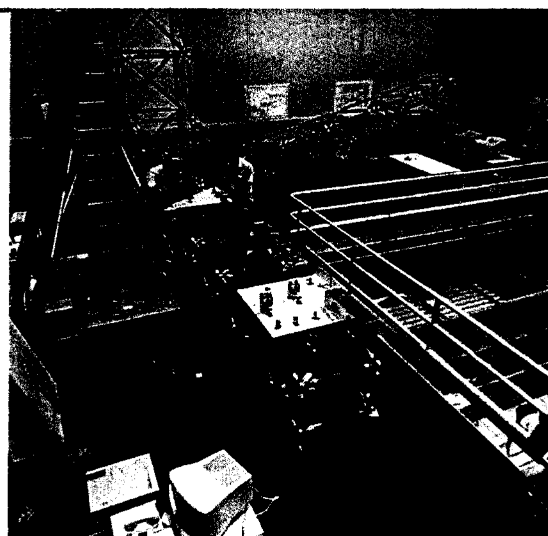

Proof-of-Concept Laser Gauge (1993)

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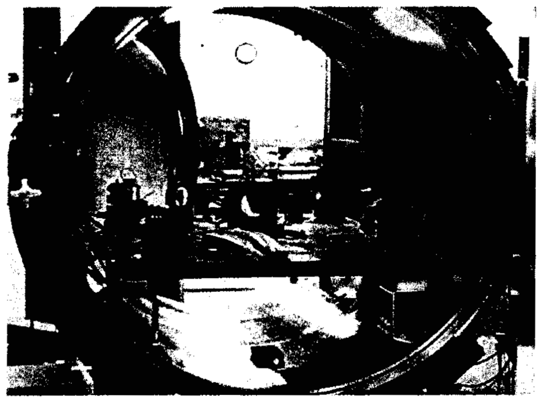

- Work performed by Shao's group under Code S funding
- Code X dictum -- CSI was not a sensor program

Interferometry Technology Program (ITP)

SIM Space Interferometry Mission

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- CSI morphed into ITP when NASA transferred technology development to Code S in 1995
  - Focus became more near-mid term than mid-long term
  - Bonds to OSI/SIM became much stronger
    - Metrology technology development began in earnest
    - However, ITP remained in JPL's Technology Programs Directorate through FY'98
  - Funding increased -- averaging about $10M/yr during FY'96 - FY'98
- ITP became an arm of the SIM Project starting in FY'99
  - Focussed on SIM -- components and testbeds
  - ITP manager reported to the SIM project manager
  - Funding increased -- averaging over $15M/yr during FY'99 - FY'00
- ITP merged into the SIM Flight System at the beginning of the current FY to facilitate transition from tech to flight

Key ITP Technologies

JPL

Space Interferometry Mission

SIM

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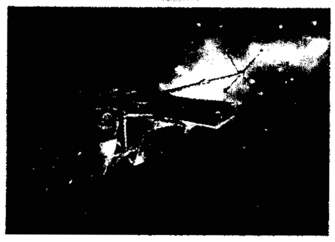
Picometer Technologies

Nanometer Technologies

Interferometer Modeling
Integrated Optical, Mechanical, Thermal, & Control

Metrology
Sub-Nanometer Relative Knowledge

Quiet Structures
Micron Stability



Starlight Fringe Detection
Sub-Nanometer Fringe Tracking

Starlight Nulling
Focal Plane Nulling: (10^{-4})

Active Optics
Nanometer Control

Interferometer I&T

Thermally-Stable Optics
Milli-Kelvin Thermal Stability

SIM Specific Components

JPL

Space Interferometry Mission

SIM

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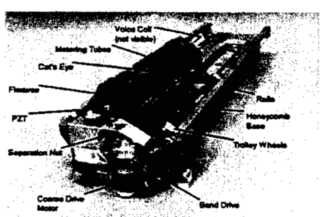
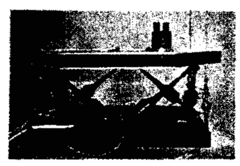
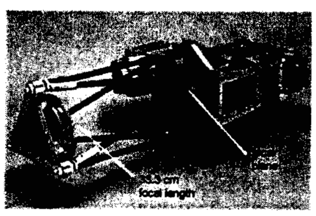


Optical Delay Line

Fast Steering Mirror



Hexapod Isolator



Astrometric Beam Combiner

Metrology Laser

Metrology Beam Launcher

SIM Specific Testbeds

JPL

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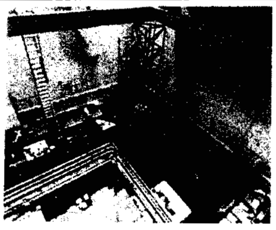
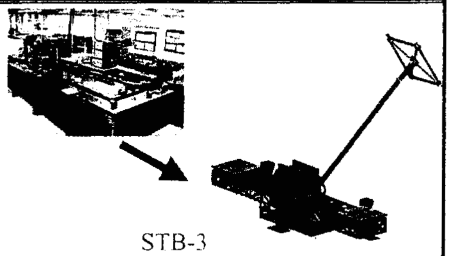
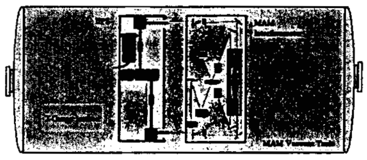


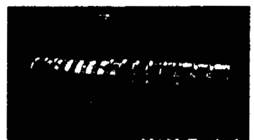
STB-1



STB-3



MAM-1



MAM Testbed

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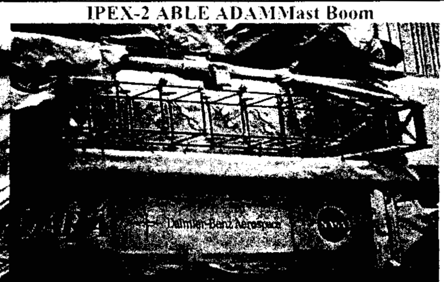
Interferometry Program Experiment (IPEX-2)

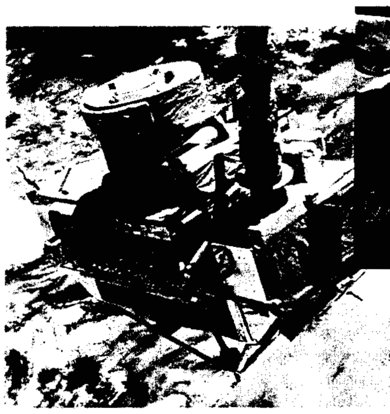
-- thermal-mechanical stability of deployable structures in space

JPL

SIM Space Interferometry Mission

IPEX-2 ABLE ADAMMast Boom





Crista-SPAS Deploys from STS-85

Launch:	15 August 1997
Sensor Complement:	24 accelerometers 24 thermistors 8 load cells 1 kHz sampling
Key Experiments:	quiet listening sun/shade transitions modal testing
Data Returned:	10 Gbytes 50 on-orbit hours
Turnaround Time:	7 months to H/W integration

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Summary

JPL

SIM Space Interferometry Mission

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- Development of interferometry technology at JPL dates to the late 1980's
- Early focus was on the nanometer stabilization technologies
  - Function of NASA HQS organization and approach at the time
- Significant effort on the picometer measurement technologies did not begin until the mid 1990's when responsibility for the technology development was transferred to Code S

Space Interferometry Mission

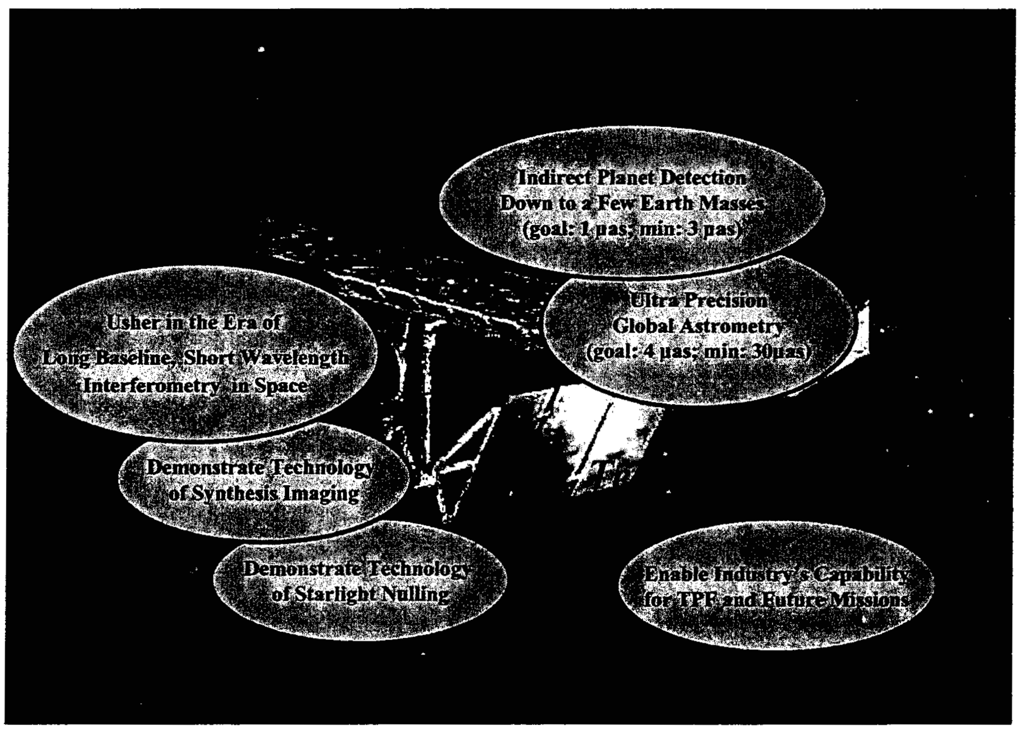
SIM

A NASA Origins Mission

External Review Board
SIM Project Overview

Tom Fraschetti
SIM Project Manager

22 & 23 March 2001



SIM as a Technology Precursor to Future Missions

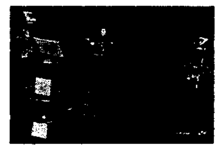
SIM Space Interferometry Mission

NASA Origins Mission

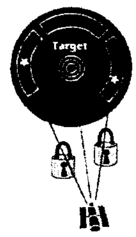
- SIM is an integral part of the flow of technology within the Origins Program and the Space Science Enterprise
  - TPF and future Planet Imaging Interferometers
  - Long baseline Interferometers from submm to X-rays (MAXIM, Stellar Imager, SPIRIT/SPECS)
- SIM is a ***unique*** technology precursor in the following areas:
  - Picometer metrology
  - Angle and pathlength feedforward
  - Rotational Synthesis Imaging

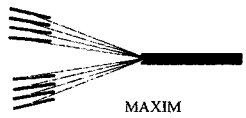
SIM is the only planned mission with the capability to identify target stars for TPF, and SIM measures the masses of planets

TPF



SPIRIT/SPECS





MAXIM

Why does TPF need SIM?

SIM Space Interferometry Mission

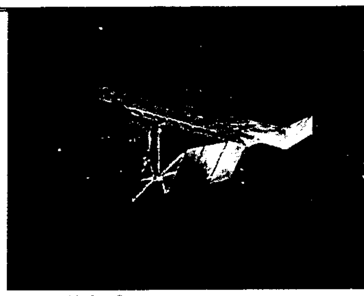
NASA Origins Mission

- SIM provides necessary technology
  - Demonstrates interferometry in space
  - Laboratory demonstration of nulling
  - Laboratory Demonstration of optical path control at one nanometer level on a large flexible structure
  - For a coronagraph system, SIM provides the technology for measuring optical wavefronts at the subnanometer level
- SIM will identify targets for TPF
  - SIM will search virtually every single star (~250) within 10 parsec for planets down to 3 Earth masses in the habitable zone. (1uas)
  - SIM will search virtually every single star (~2000) within 20 parsec for planetary systems like our own. SIM will search at 4uas sensitivity, <u>every star</u>, that TPF can detect an Earth around.
- If SIM finds an adequate number of planets within <10parsec, TPF requirements/cost could be significantly reduces
- SIM provides a critical piece of information, planet masses, for TPF science.

Space Interferometry Mission

SIM Space Interferometry Mission

A NASA Origins Mission



- What?
  - 3 collinear Michelson Stellar Interferometers
  - 10 meter baseline
  - Visible wavelength
  - Launch Vehicle: Space Shuttle or EELV
  - Earth-trailing solar orbit
  - 5 year mission life with 10 year goal
  - SIM is a JPL, Caltech, Lockheed Martin, and TRW partnership
- Why?
  - Perform a search for other planetary systems by surveying 2000 nearby stars for astrometric signatures of planetary companions
  - Improve best current catalog of star positions by >100x and extend to fainter stars to allow extension of stellar knowledge to include our entire galaxy
  - Study dynamics and evolution of stars and star clusters in our galaxy to understand how our galaxy was formed and how it will evolve.
  - Calibrate luminosities of important stars and cosmological distance indicators to improve our understanding of stellar processes and to measure precise distance in the distant universe

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SIM Space Interferometry Mission

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The SIM Partnership: Many Partners

One Team

LOCKHEED MARTIN

Metrology Subsystem
Starlight Subsystem
Interferometer I&T
Interferometer Operations

TRW

Spacecraft
Precision Support Structure
Assembly, Test, & Launch Operations
S/C Operations

Interferometry Science Center

Science Data Analysis and Archiving
Science Operations
Science Planning
Science Community Interface
Outreach

SIM Science Team
UC Berkeley
JPL
Ohio State University
Raytheon ITSS
USNO
Dartmouth College
Georgia State University
University of Virginia
Caltech
St. Ambrose University
UC San Diego
STScI

JPL

Project Management
System Engineering
Integrated Modeling
Real Time Control Subsystem
Mission Systems
Mission Assurance
Risk Management

Project Organization & Personnel

JPL

SIM Space Interferometry Mission

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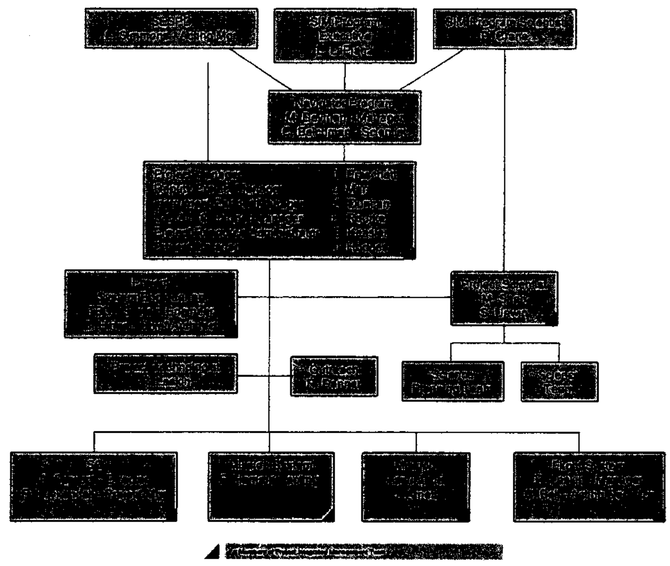
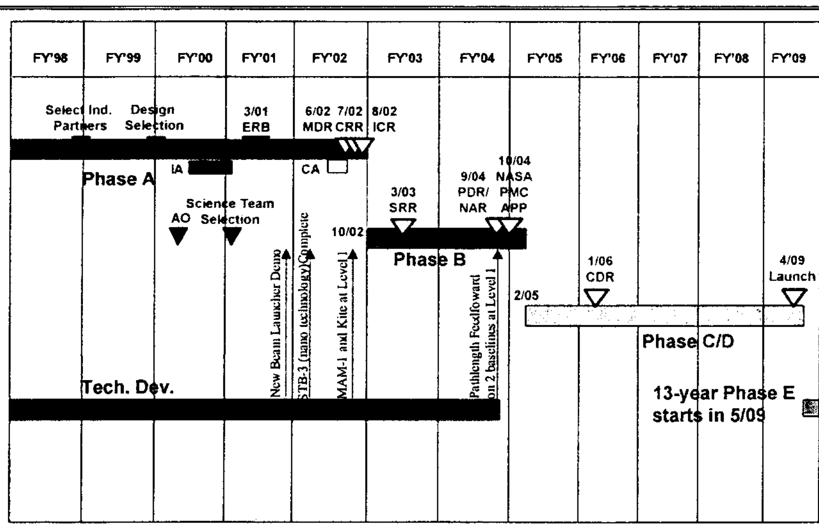


SIM Project Schedule

JPL



ATLO = Assy, Test & Launch Ops
CA = Confirmation Assessment
CDR = Critical Design Review
CR = Confirmation Review (NASA PMC)
ERB = External Review Board
IA = Independent Assessment
I&T = Integration & Test
MDR = Mission Definition Review
NAR = Non Advocate Review
PDR = Preliminary Design Review
NASA PMC = Programmatic Management Council (APP = Approved)
SRR = System Requirements Review
CRR = Confirmation Readiness Review (JPL PMC)
ICR = Initial Confirmation Review (Code S)

Industry Involvement in SIM

SIM Space Interferometry Mission

A NASA Origins Mission

- FY97 - TRW, Lockheed Martin, and Ball selected for Pre-Phase A studies
  - Each developed design options for SIM
  - Design options were presented and reviewed
  - SIM baseline architecture established
- FY98 - Project entered Phase A
  - October 1997 Code S Phase A initiation letter signed
- Decision was made to select Industry Partners immediately
  - Complexity of SIM required technical strengths of JPL and industry
  - Effective technology transfer required early industry involvement
- RFP issued and Industry Partners selected in FY98, with funding start at the beginning of FY99
- Industry involvement has been invaluable for both the technology development and the flight design
- The SIM Science Team was selected in the Fall of 2000

SIM Cost History

SIM Space Interferometry Mission

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- FY97 Initial Plan Review (IPR) was the first bottoms up cost-to-complete for SIM ($450M Phase C/D only, real year $, no launch vehicle cost)
  - Very low design maturity
  - Early SIM Classic configuration, Delta-II launch into 900km sun-sync Earth orbit
  - Costed as JPL in-house build
- March 2000 cost estimate ($870M Phase C/D only, real year $, no launch vehicle cost)
  - Substantial improvement in design maturity
  - SIM Classic design
  - EELV launch into ETSO
  - Full Industry Partners (IP) participation
  - Costed as JPL-IP implementation mode

Instruction Letter from Code S

SIM Space Interferometry Mission

A NASA Origins Mission

- Letter from Dr. Weiler to Ed Stone dated 10/27/00, set a Phase B/C/D cost cap of $930M in FY01 dollars for SIM.
  - Cost cap includes launch vehicle cost or Shuttle-related costs
  - Budget reserves defined (15% for Phase B, 40% for Phase C/D, 10% for EELV, 20% for Shuttle-related costs)
- Level 1 science requirements in the SIM Formulation Authorization Document are now goals. Project to propose new Level 1 science requirements
  - Proposed mission concepts must demonstrate scientific uniqueness and not duplicate science from any other planned mission
  - Scientific results must ID potential science targets for TPF
- Technology flight demos only for TPF and only if requires space environment
- Project to develop design options, with the SIM Science Team, that meet the cost cap
  - Science capability for each design option must be defined
  - Project to determine the cost for each option and viable top level schedule
- IA to rerun Independent Cost Estimate/Risk Assessment on proposed design options
  - Independent Cost Estimate must be within 20% of Project cost estimates for each option
- Project to report to a Code S convened External Review Board in March and April (now slipped to May)

Charge to the Team

SIM Space Interferometry Mission

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- Develop one design concept that preserves as much of the SIM science as possible within the $930M cost cap
- Develop a second, minimum, planets only, design concept that will provide a cost substantially ($100M - $150M) below the cost cap
- Develop a third concept somewhere in between the first two

Study Results

JPL

SIM Space Interferometry Mission

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- The SIM team has developed three design options with varied science capability
- The cost for all three design options are under the $930M cost cap
- All three design options resulted in not only a sizeable cost savings, but even a larger cost and technical risk savings
  - External metrology system greatly reduced (50% reduction in external metrology beams)
  - 50% reduction in overall mechanism count
  - Significant reduction in optical complexity
- IA Independent Cost Estimate is well within 20% of our estimate for all designs
- Cost delta between the highest and lowest cost option is only about $50M
- **Our SIM Technical Advisory Board concluded that the complexity of SIM is now on a par with other systems that have flown in space**

Mission Concept Options

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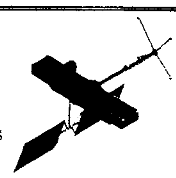
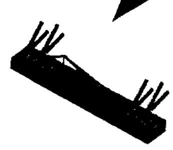
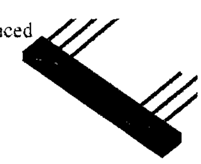
- Reference Design
  - This is the design which was reviewed by the IA team
  - Project costs based on this design
  - Not being considered further as it does not meet the budget guidelines



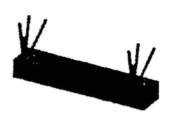
- Shared Baseline SIM
  - Best understood design
  - Maintains over 90% of Reference Design science
  - Maintains Grid capability
  - Some imaging science, and no nulling



- ParaSIM
  - Same astrometric capability as Shared Baseline but with greatly reduced science throughput
  - Provides only about 30% to 50% of Reference Design science
  - Minimal imaging demonstration (no science), and no nulling



- SONATA
  - Planet finding only, no Grid
  - Provides only about 20% of Reference Design science
  - Minimal imaging demonstration (no science), and no nulling



The Bottom Line

- The "knee" of the science vs cost curve for interferometry appears to be at Shared Baseline
  - The maximum cost reduction was achieved with a very small loss in science
  - Moving from Shared Baseline to the other design options provides a very small decrease in cost for a very large loss in science

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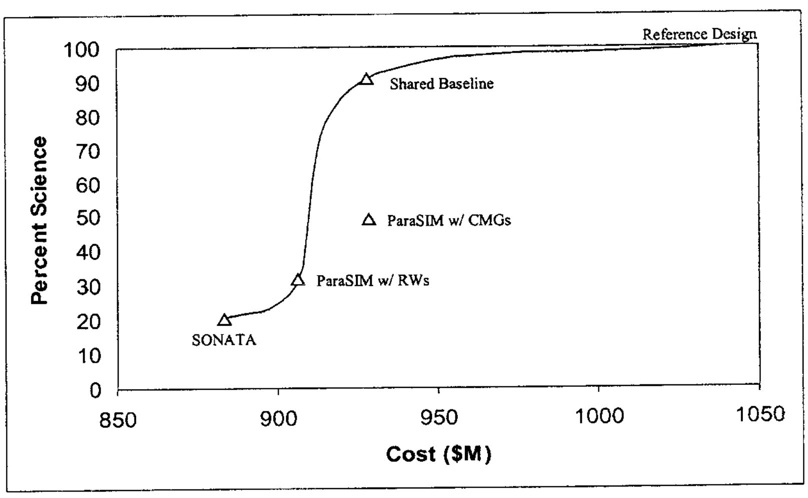
Science Vs Cost Plot



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The Bottom Line

Space Interferometry Mission

SIM

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- The "knee" of the science vs cost curve for interferometry appears to be at Shared Baseline
  - The maximum cost reduction was achieved with a very small loss in science
  - Moving from Shared Baseline to the other design options provides a very small decrease in cost for a very large loss in science
- There was no "planets-only" design that provided a substantial ($100M to $150M) cost reduction below the cap

Is there a Lower Cost Planets-only Approach

Space Interferometry Mission

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- We have thoroughly explored the trade space for the SIM interferometer architecture and found no low cost option
  - We looked at variable baseline lengths from 8 meters on a fixed structure to 100 meters on deployable booms
  - The Independent Assessment team has independently looked at a deployable concept that did not offer a cost savings
  - We have looked at design variations and settled on three representing the lowest cost approaches
- Other astrometric architectures such as FAME and GAIA are significantly less sensitive for planet detection (250X and 30X respectively). The cost for scaling up GAIA would far exceed the SIM cost
- Large filled aperture telescopes to detect planets to a few earth masses in a 1AU orbit would be comparable to TPF or perhaps next generation TPF
- Only the SIM architecture will give the mass of any planet it detects
- **SIM is the lowest cost architecture, and Shared Baseline offers the best science value**

The Bottom Line

- The "knee" of the science vs cost curve for interferometry appears to be at Shared Baseline
  - The maximum cost reduction was achieved with a very small loss in science
  - Moving from Shared Baseline to the other design options provides a very small decrease in cost for a very large loss in science
- There was no "planets-only" design that provided a substantial ($100M to $150M) cost reduction
- Shared Baseline offers the largest science return
  - It provides the very best science value per dollar
  - It is the first choice of our Science Team
  - It provides the highest probably of maintaining science community support for SIM
- Shared Baseline is the most robust design
  - It can gracefully degrade to ParaSIM mode on orbit if multiple failures occur
- **SIM Project recommends the Shared Baseline design**

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SONATA is Not an Acceptable Option

- SONATA is the highest risk of the three options
  - It is a more radical design approach
  - It require full aperture metrology (FAM) which will be a technical challenge
  - It does not have the capability to do a Grid
  - Interferometer integration and test will require telescope reconfiguration (if it is possible)
- The cost delta between ParaSIM and SONATA is only $20M
  - The cost risk between SONATA and either of the other options is much higher
  - A six month schedule slip due to FAM problems would easily consume the $20M cost difference between SONATA and ParaSIM
- The science performance is not acceptable for the cost
  - SONATA is only capable of about 20% of the Reference Design science, with no wide angle astrometry or Grid capability
  - Science throughput is less than Shared Baseline for planet finding
  - Dramatically reduced capability to detect long period planets (20X less sensitivity)

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Level 1 Science Requirements

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SIM

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- These science requirements were established by NASA Headquarters based on the SIM Science Working Group Final Report
- The Level 1 Science Requirements are documented in the SIM Formulation Authorization dated January 28, 2000, and were contained in the science AO
- The Shared Baseline and ParaSIM maintain both of these requirements, but ParaSIM's throughput is considerably less. SONATA does *only* Narrow Angle Astrometry, and with less throughput than Shared Baseline
- These Level 1 science requirements will remain the same

SIM Science Requirements		
	Minimum Requirement	Goal
Narrow Angle Astrometry	3 μas amplitude (1 sigma) in a single measurement over a 1 deg FOV. Target and four reference stars as faint as V=12 mag in < 1 hr for a measurement in one orientation	1 μas amplitude (1 sigma) in a single measurement over a 1 deg FOV. Target and four reference stars as faint as V=12 mag in < 1 hr for a measurement in one orientation
Global Astrometry	Better than 30 μas (1 sigma) at end of 5 year mission over the entire sky for stars brighter than V=20 mag.	4 μas (1 sigma) at end of 5 year mission over the entire sky for stars brighter than V=20 mag.

Level 1 Technology Requirements

JPL

Space Interferometry Mission

SIM

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- These technology requirements were established by NASA Headquarters and documented in the SIM Formulation Authorization dated January 28, 2000, and were contained in the science AO
- The updates to these requirements are design independent

SIM Technology Requirements	
Use of Interferometry Techniques	Demonstrate a space interferometer system (with long baseline operating in short wavelength) having capability of active pathlength stability control and pathlength knowledge consistent with the astrometric science goals
Demonstration of Synthesis Imaging	Provide "uv-plane" coverage adequate to image ~~up to 50~~ a few point sources located within a 2 arcsec field ~~the approximate 1 degree primary beam of a single telescope, e.g. for imaging the core of a globular cluster.~~
~~*Demonstration of Starlight Nulling*~~	~~Better Active pathlength control and nulling instrumentation adequate to reduce the intensity of light in a ≥20% spectral bandwidth from a star by a factor of 10^4 for proiods as long as 1 hour.~~

Five Key Questions

1. Does SIM fit in the larger framework of other missions and other techniques? ***YES***
   - SIM does unique science that no other planned mission can/will do
   - TPF needs SIM (technology, target identification, planet masses)
2. Is SIM feasible from an engineering and technology perspective? ***YES***
   - SIM new design is much less complex and risky than the Reference Design, and is now no more complex than missions that have successfully flown (per the SIMTAC)
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap? ***YES***
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets? ***NO***
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry? ***YES***
   - This capability allows SIM to detect long-period (>5 year) planets necessary for TPF
   - Global Astrometry is a key science capability endorsed by the Decadal Reports

SIM Space Interferometry Mission

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Backup

SIM Space Interferometry Mission

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SIM Technical Advisory Committee

- Richard (Dick) Dyer
  - VP Reconnaissance Technologies, Schafer Corp
- David (Dave) Miller
  - Professor and Director Space Systems Lab, MIT
- David (Dave) Mozurkewich
  - Remote Sensing Lab, NRL
- M. Charlie Noecker
  - Ball Aerospace and Technologies Co
- Robert (Bob) O'Donnell
  - MRJ, Inc

SIM Space Interferometry Mission

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SIM Science Team

Key Science Projects

Names	Institutions	Topic
Dr, Geoffrey Marcy	University of California, Berkeley	Planetary Systems
Dr. Michael Shao	NASA/JPL	Extrasolar Planets
Dr. Charles Beichman	NASA/JPL	Young Planetary Systems and Stars
Dr. Andrew Gould	Ohio State University	Astrometric Micro-Lensing
Dr. Edward Shaya	Raytheon ITSS Corporation	Dynamic Observations of Galaxies
Dr. Kenneth Johnston	U.S. Naval Observatory	Reference Frame-Tie Objects
Dr. Brian Chaboyer	Dartmouth College	Population II Distances & Globular Clusters Ages
Dr. Todd Henry	Georgia State University	Stellar Mass-Luminosity Relation
Dr. Steven Majewski	University of Virginia	Measuring the Milky Way
Dr. Ann Wehrle	NASA/JPL	Active Galactic Nuclei
	Mission Scientists	
Dr. Guy Worthey	St. Ambrose College	Education & Public Outreach Scientist
Dr. Andreas Quirrenbach	University of California, San Diego	Data Scientist
Dr. Stuart Shaklan	JPL	Instrument Scientist
Dr. Shrinivas Kulkarni	California Institute of Technology	Interdisciplinary Scientist
Dr. Ronald Allen	Space Telescope Science Institute	Imaging and Nulling Scientist

SIM Space Interferometry Mission

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SIM Space Interferometry Mission

Intro to Interferometry and The SIM Reference Design

Brad Hines
Interferometer Architect
March 22, 2001

with acknowledgement to previous architect Jeffrey Yu

A NASA Origins Mission

Outline

JPL

- Interferometry Overview
  - Motivation for interferometry
  - What is an interferometer?
  - How do you use one to do science?
  - How do you build one?
- SIM Mission Reference Design

SIM Space Interferometry Mission

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What is Interferometry?

- For our purposes today, it's a way of making high-resolution measurements
- Measures properties of the light from an object that we then use to understand properties of the object
- Sometimes this is an image, but often something less ambitious

Space Interferometry Mission
SIM
A NASA Origins Mission

Motivation for Interferometry
Large Aperture --> High Resolution

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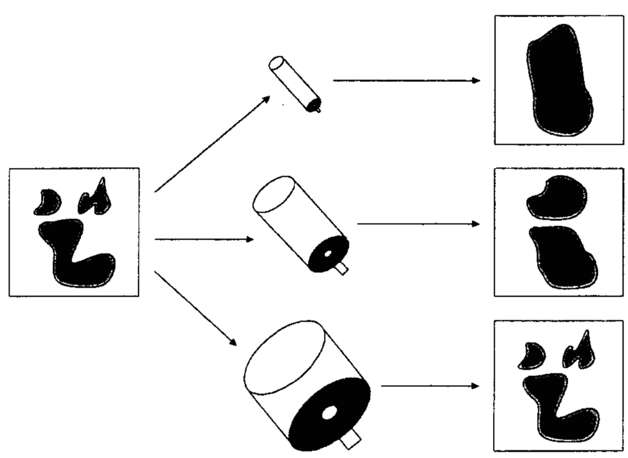

What is an Interferometer and What Does It Do?

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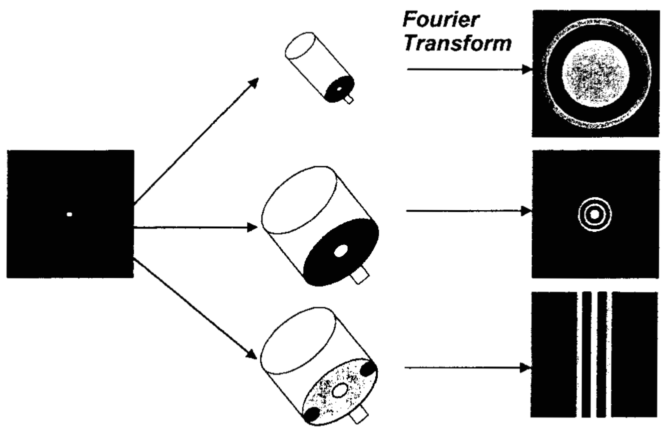

Synthetic Aperture Imaging with an Interferometer

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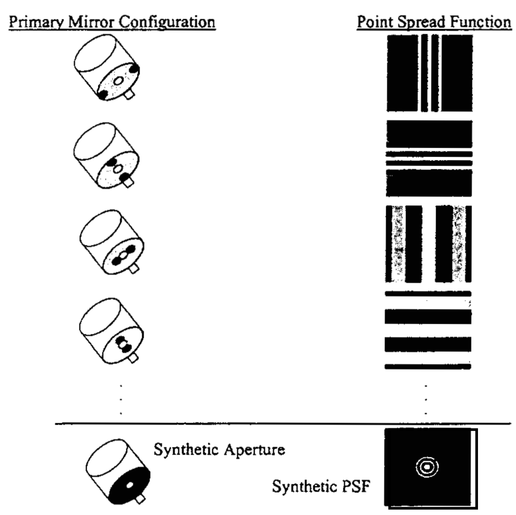

Fizeau vs. Michelson

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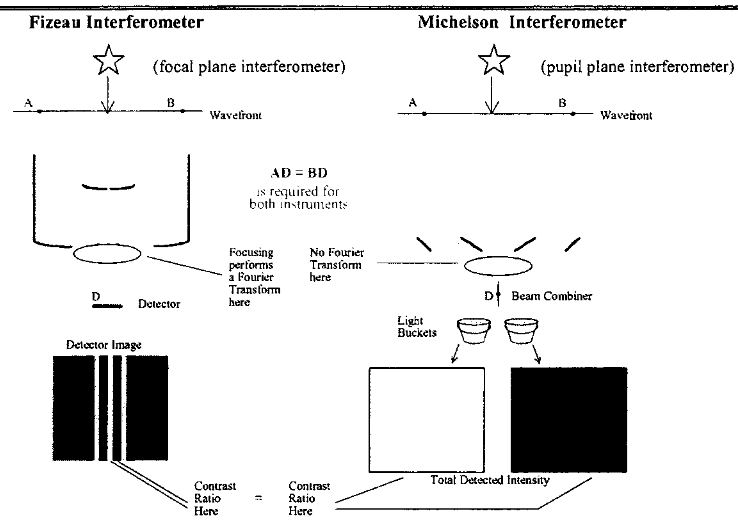

"VISIBILITY"

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Pointing an Interferometer

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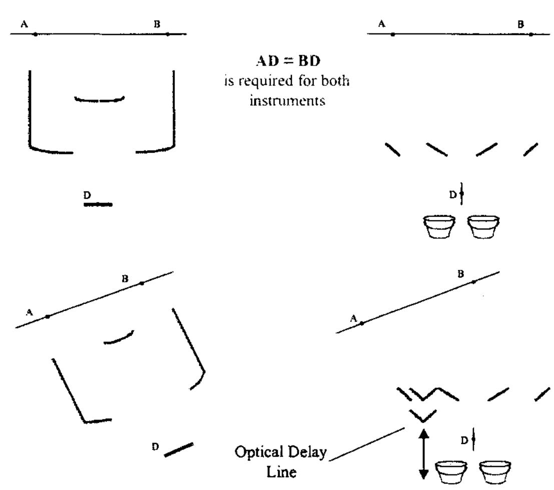

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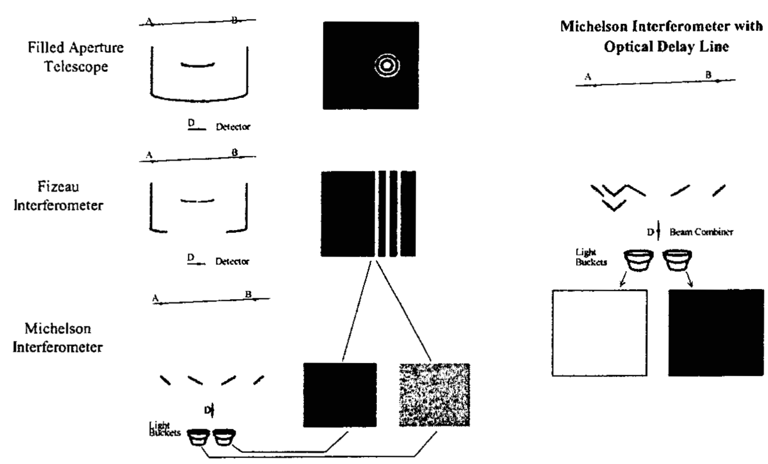
Astrometry
Where is the Star in the Sky?

JPL

Space Interferometry Mission

SIM



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Astrometry with a Michelson Inteferometer

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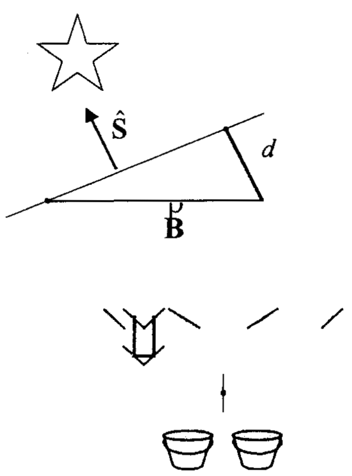

- For perfect interference, we must have $d = \hat{S} \cdot \vec{B}$.
- If we know $\hat{S}$ and $\vec{B}$, we know what to set d to.
- Conversely, if we know $\vec{B}$ and measure d, we can learn something about $\hat{S}$.
- If we do this for 3 different values of $\vec{B}$, we can completely determine $\hat{S}$.

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The Fringe Pattern

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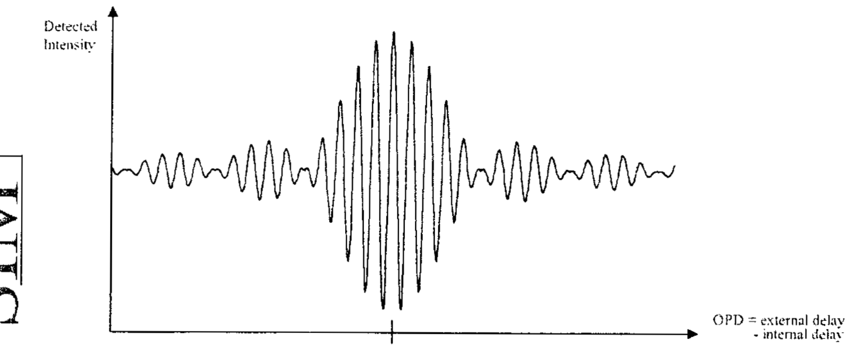
- As the delay line moves away from an exact pathlength match, the detected intensity modulates



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Fringe Detection Techniques 1 - Pathlength Dither

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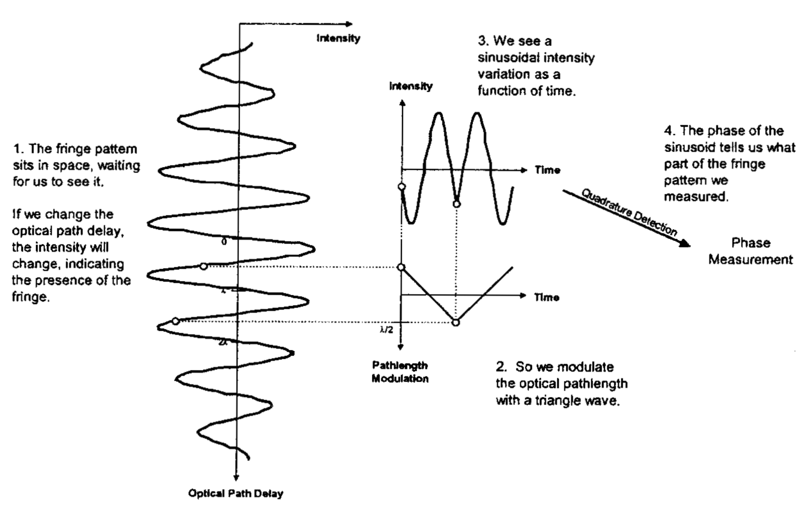

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Fringe Visibility

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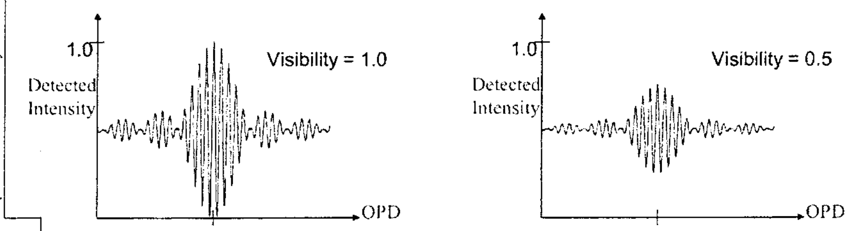
- How close to perfect is the interference?



- Visibility can be affected by
  - Imperfections in the interferometer
  - The interaction between the object and the baseline

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Model-Based Imaging

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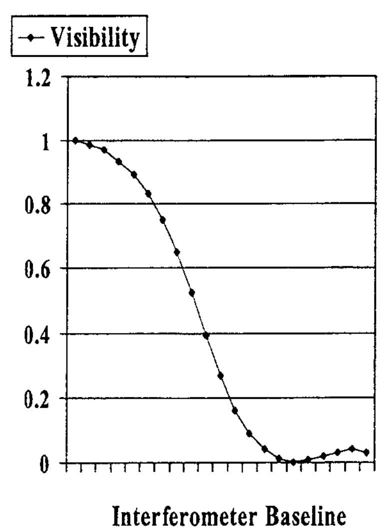
- If you know something about the object a priori, you don't have to make a full image
- Example - Uniform disk



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Fringe Detection Techniques 2 - Dispersed Fringe

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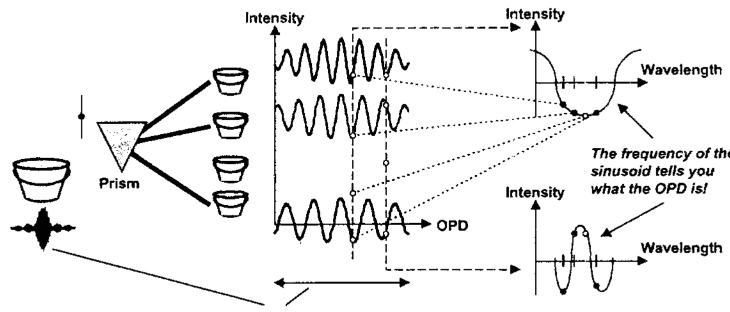
- Instead of one light bucket, use different buckets for different wavelengths



Since the spectral bins are narrow (more like laser light), the fringe envelope is wider. So the fringe detection range of the dispersed fringe detector is much greater.

Necessary Conditions for Making Observations

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Telescope (a single Keck)

- λ/20 optical precision
- Segments pointed correctly
- Segment piston errors zeroed

Michelson interferometer

- λ/20 optics, stable to 10 nm
- Wavefront tilt in each arm equal
- Delay line adjusted for equal pathlength

Building the Real Thing - Required Systems

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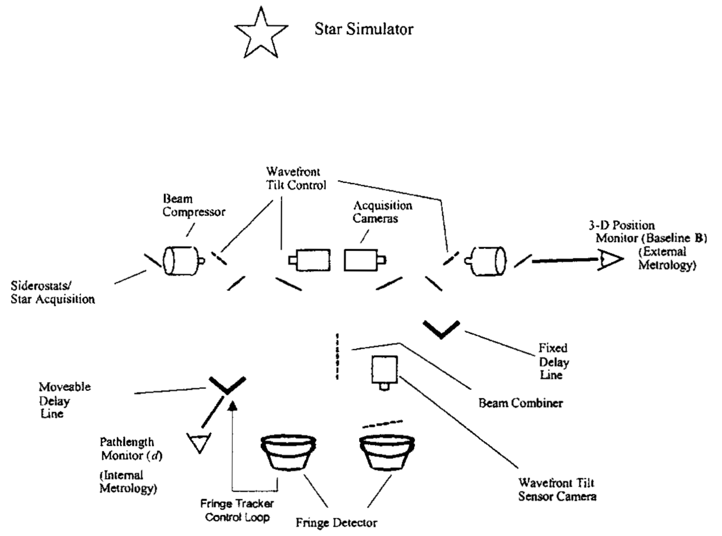

The Role of Computers

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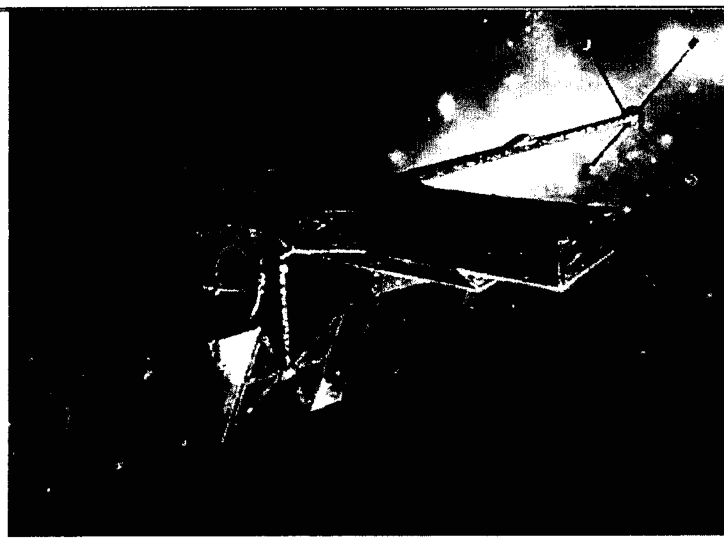
- Michelson measured fringes with his eyeball as atmospheric turbulence swept them by
- Modern computers allow quick fringe measurement before the fringe moves, allowing *fringe tracking*
- Computers also handle the complex sequencing of the subsystems

SIM Reference Design



Key Flight System Requirements for SIM Reference Design

- Science Objectives
  - Astrometry
    - 4 uas wide angle (15 degrees) mission accuracy
    - 1 uas narrow angle (1 degree) mission accuracy
  - wavelength - 0.4 - 0.9 um
  - minimum brightness - 20th mag
  - less than 120 degrees of the celestial sphere is inaccessible at any time
- Technology Objectives
  - Imaging => ~0.5 meter to ~10 meter baselines with "uniform" u-v coverage
  - Nulling Technology Demonstration => 10^{-4} null over 5 minutes
- Flight Environment Requirements
  - Atlas V 421 Launch Vehicle => 5318 kg launch capability
  - Earth - trailing orbit
  - 5 year lifetime

SIM Astrometric Measurement

Space Interferometry Mission

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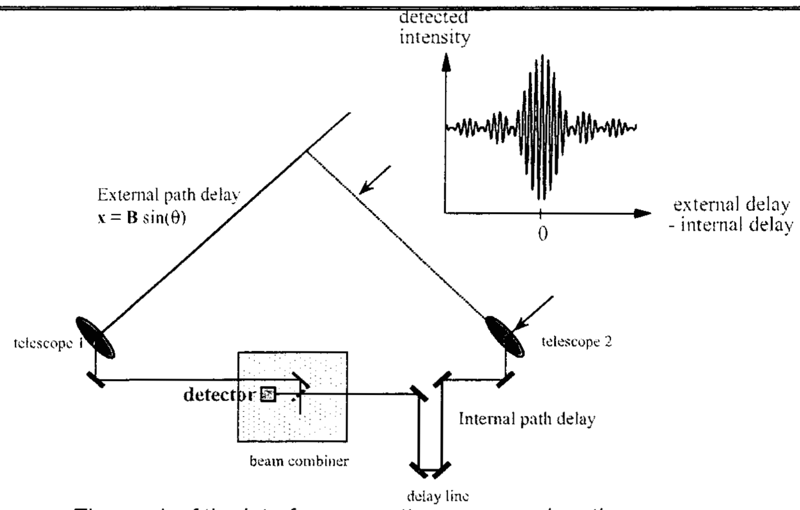

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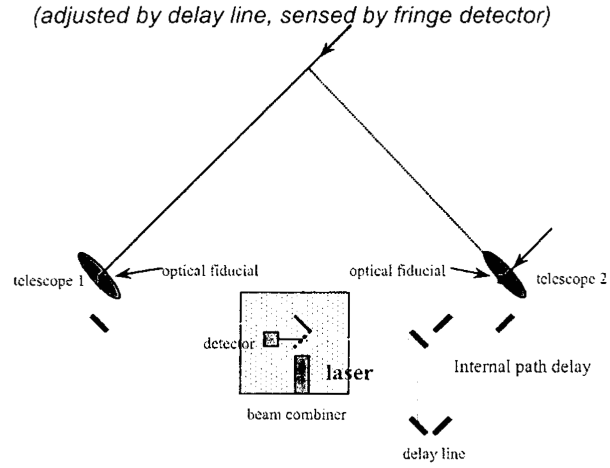
The peak of the interference pattern occurs when the internal path delay equals the external path delay

Internal Metrology

Space Interferometry Mission

SIM

Laser gauge measures internal delay
(adjusted by delay line, sensed by fringe detector)



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Laser path retraces starlight path from combiner to telescopes

External Metrology

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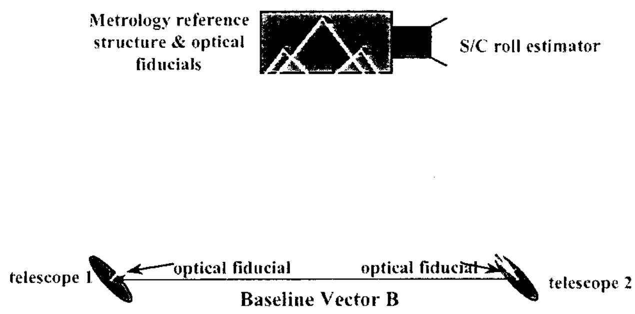
Measure baseline B using laser triangulation



Baseline is determined in frame of metrology reference structure, as determined by "roll sensor"

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External Metrology

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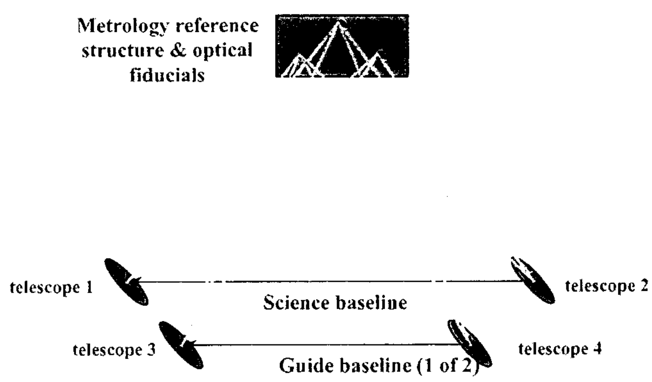

The attitude information is used to stabilize the science interferometer by commanding its optical delay line

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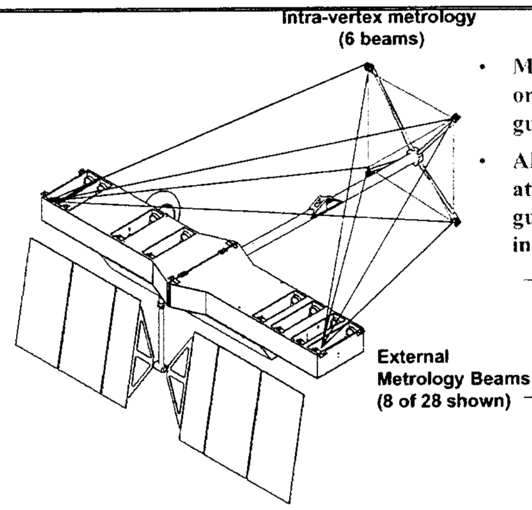
External Metrology



- Measures relative orientation of science and guide baselines
- Allows accurate transfer of attitude information from guides to science interferometer
  - Science interferometer stabilized by commanding its delay line
  - Provides long integration time for faint stars

SIM Space Interferometry Mission

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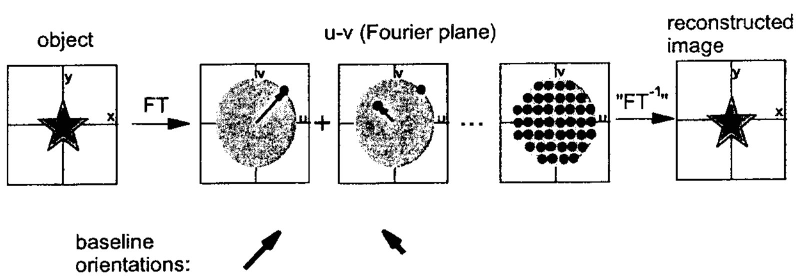
Imaging with an Interferometer



- The interferometer measures the Fourier transform of the object
- Each baseline orientation selects one point in the (u,v) plane
  - The data for this point is the fringe visibility and phase
- With many baseline orientations, you fill in the (u,v) plane
- The image is reconstructed from these Fourier-domain measurements

SIM Space Interferometry Mission

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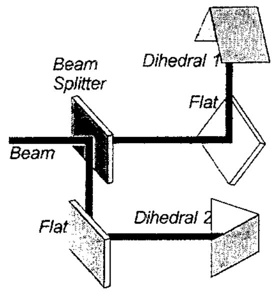
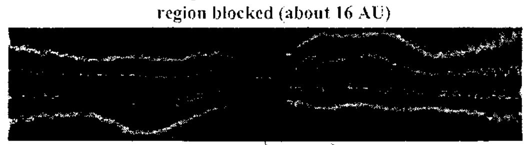
How SIM Performs Nulling

Space Interferometry Mission

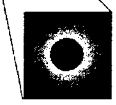
SIM



HST image of Beta Pictoris with central region blocked (about 16 AU)



SIM will only null out the starlight in the central 1 AU region



- In the nulling beam combiner, flip the phase of one arm of the interferometer before combining the beams
- Light that comes in on axis *is sent back to the star*
- Rejection falls off as the square of the angle
- Pathlength must be stable to about 1 nm

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SIM Design Summary

Space Interferometry Mission

SIM

- Three simultaneous interferometers
  - 2 Guides, 1 Science
- Three separate interferometer baseline
  - Optical path delay is introduced in one arm of the interferometer.
  - Pointing control system minimizes differential wavefront tilt between two interferometer arms.
  - Pathlength control system maintains differential pathlength at zero fringe position
- Switchyard interferes any combination of collectors
  - allows measurements at different baseline lengths
- External metrology monitors changes between three baselines
- Internal metrology measures starlight OPD from corner cube to beam splitter
  - subaperture metrology scheme - metrology only measures central portion of starlight beam
- External and internal metrology share common fiducial

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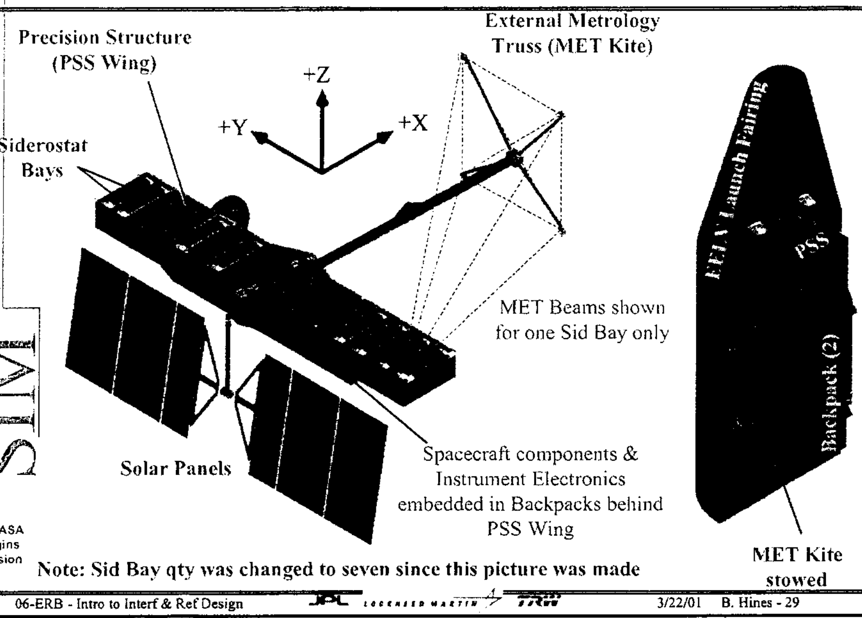
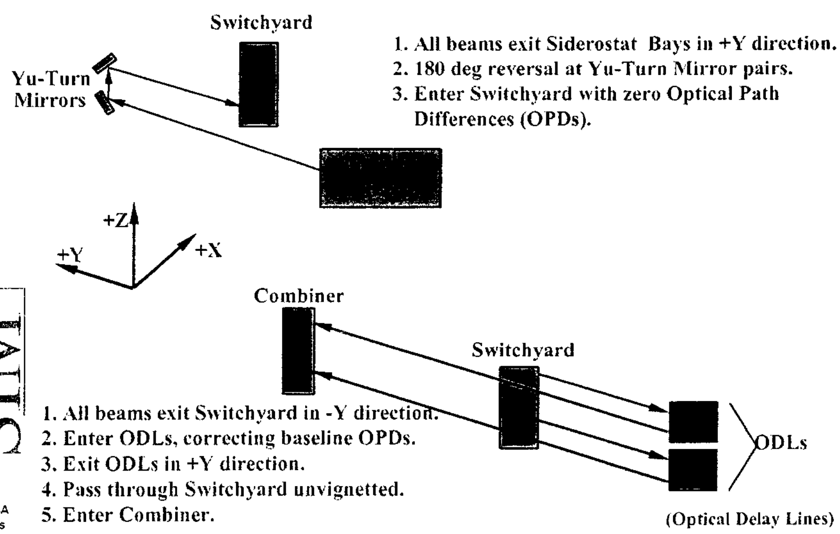
SIM Configuration



SIM Space Interferometry Mission
A NASA Origins Mission

Note: Sid Bay qty was changed to seven since this picture was made

Light Paths Through Instrument



1. All beams exit Siderostat Bays in +Y direction.
2. 180 deg reversal at Yu-Turn Mirror pairs.
3. Enter Switchyard with zero Optical Path Differences (OPDs).

1. All beams exit Switchyard in -Y direction.
2. Enter ODLs, correcting baseline OPDs.
3. Exit ODLs in +Y direction.
4. Pass through Switchyard unvignetted.
5. Enter Combiner.

SIM Space Interferometry Mission
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Instrument Layout

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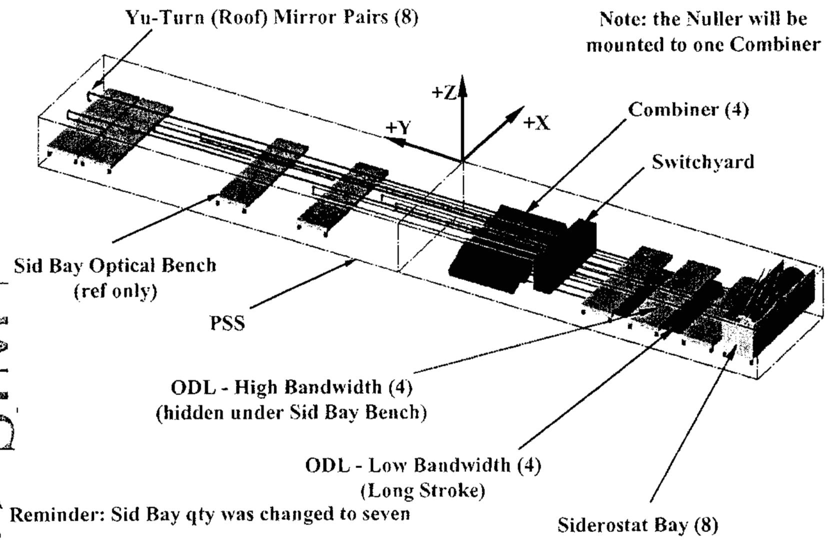
SIM
Space Interferometry Mission



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Reminder: Sid Bay qty was changed to seven

Metrology Kite & Boom

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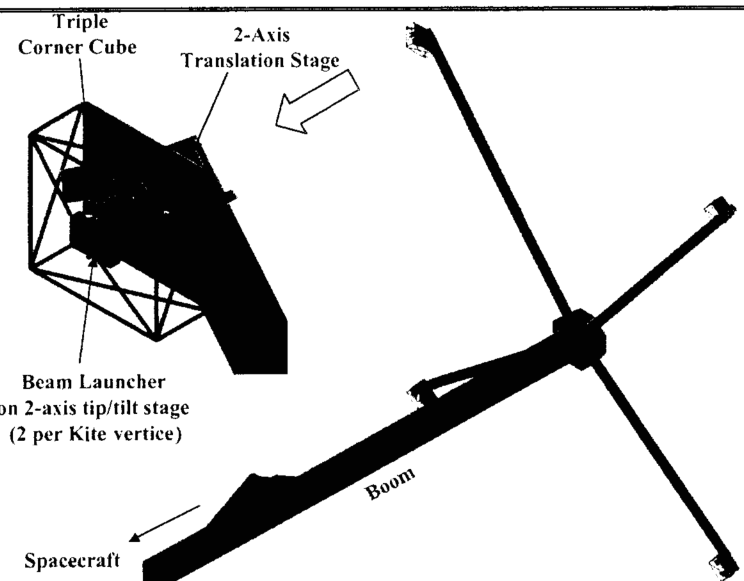
SIM
Space Interferometry Mission



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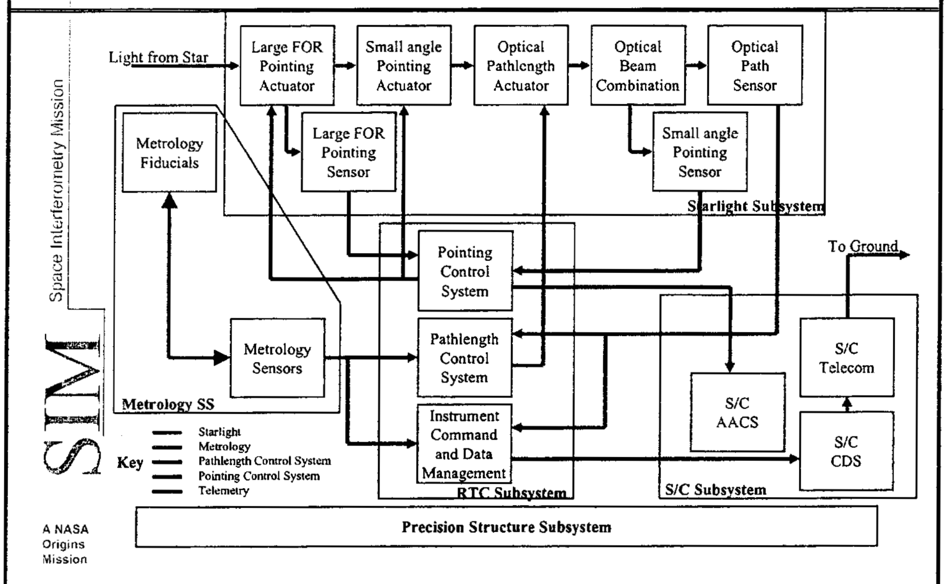
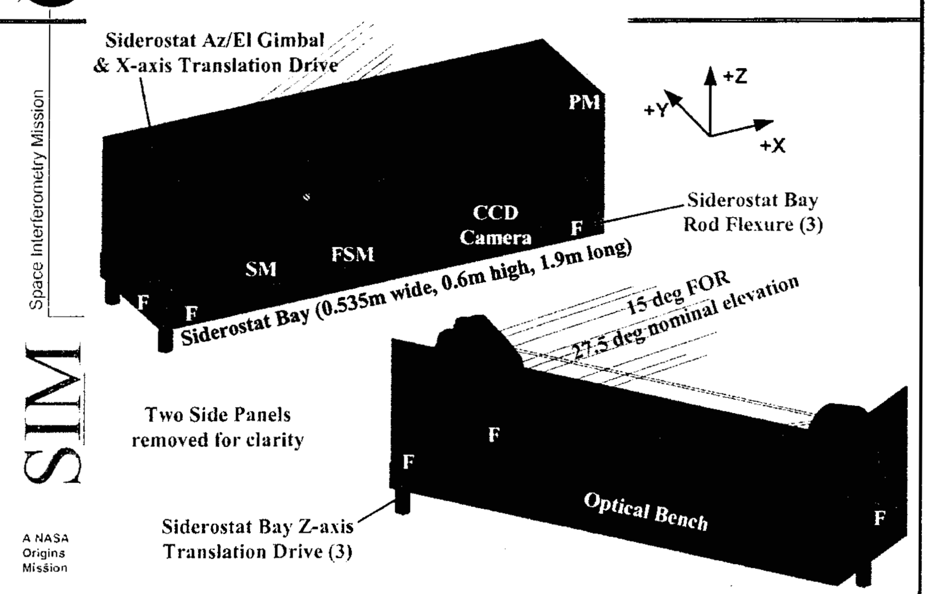
Flight System Functional Block Diagram



Siderostat Bay Configuration



Optical Delay Line (ODL)

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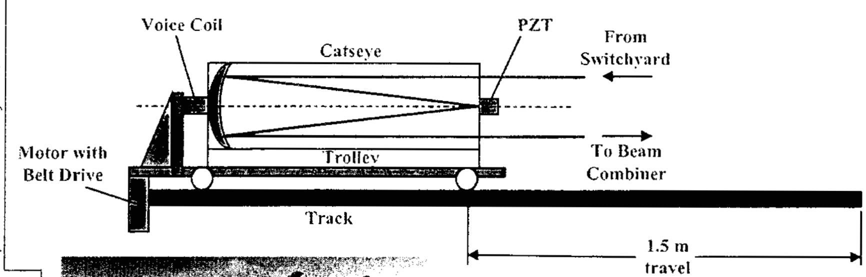

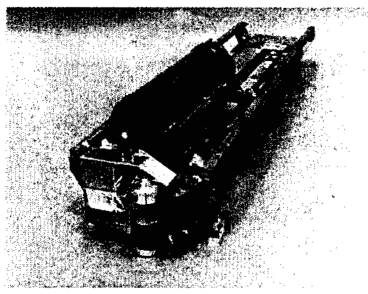

SIM

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SIM Astrometric Beam Combiner

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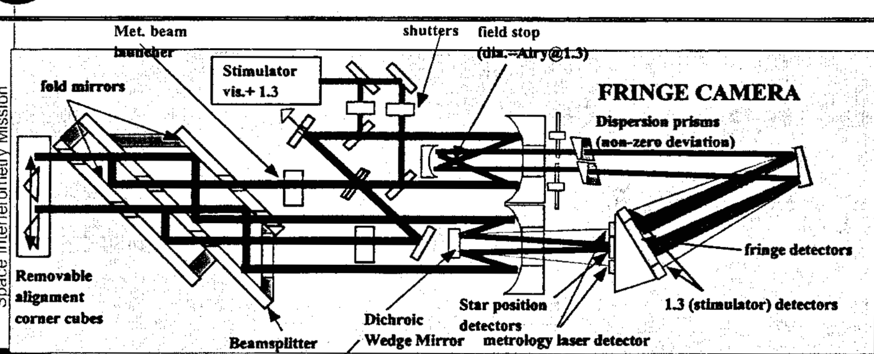

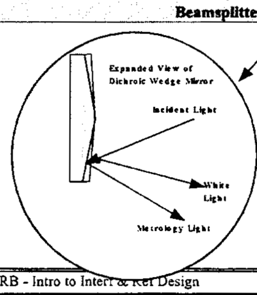

SIM

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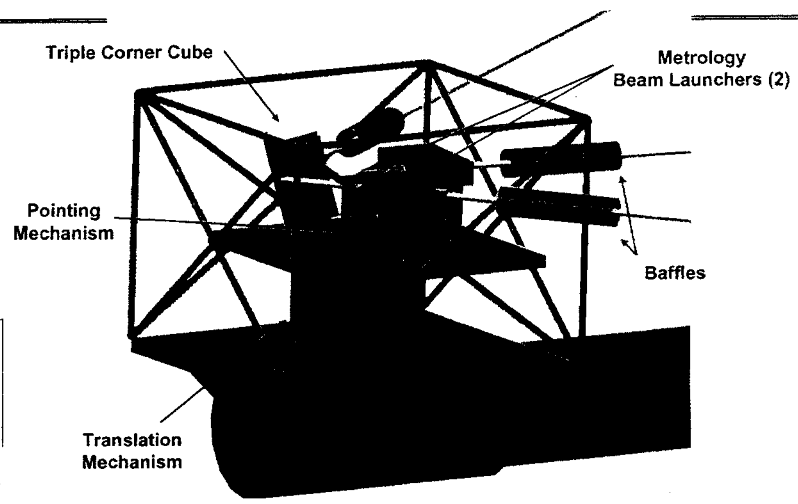
Metrology Vertex

Space Interferometry Mission

SIM



Beams from sid bay not shown

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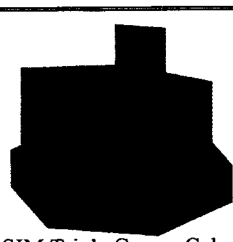
Mission

Metrology Fiducials

Space Interferometry Mission

SIM



SIM Triple Corner Cube

Siderostat Corner Cube

Prototype TCC

- External metrology Triple Corner Cube
  - $<\lambda/20$ p-v surfaces
  - < 1 as dihedral error
  - < 1 um alignment of vertices
- Siderostat corner cube
  - $<\lambda/30$ p-v surfaces
  - < 0.5 arcsec dihedral error
  - < 10 um vertex to sid surface placement
  - < 2 nm vertex to sid knowledge

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Mission

SIM Electronics Block Diagram

Space Interferometry Mission

SIM

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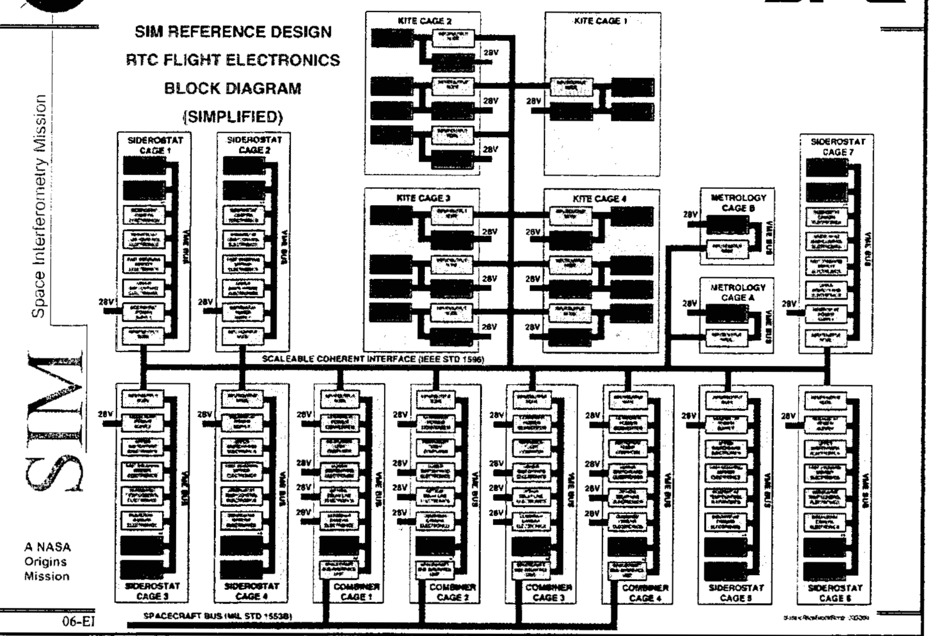

Metrology Boom Deployment Mechanism Concepts

Space Interferometry Mission

SIM

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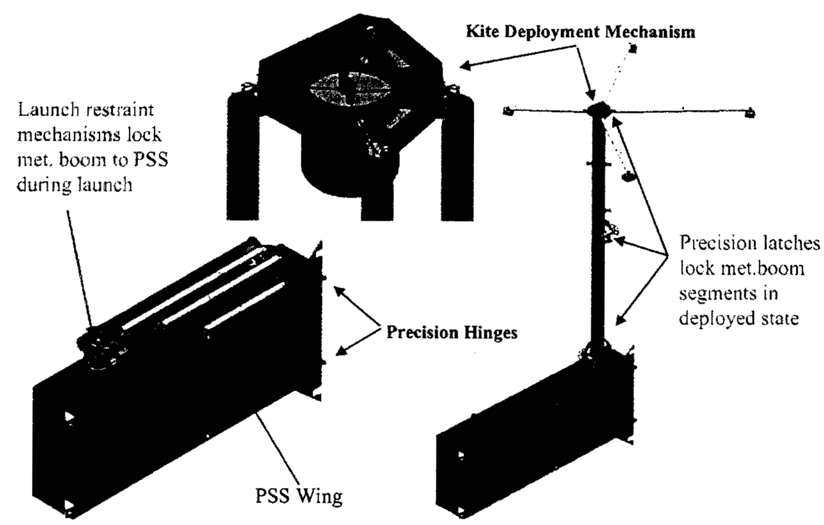

SIM Reference Design Performance
Wide Angle

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SIM Space Interferometry Mission

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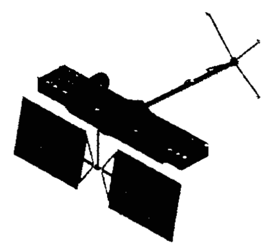
5-Yr Mission Accuracy 183.65 pm 3.79 µas
Single Look Accuracy 497.79 pm 10.27 µas

- 1.1 External Metrology 81.46
  - 1.1.1 Science External Metrology Error 27.83
  - 1.1.2 Guide External Metrology Error 16.78
  - 1.1.3 Tetrahedron External Metrology Error 73.84
  - 1.1.4 Absolute External Metrology Error 13.50
- 1.2 Guide Interferometer 205.25
  - 1.2.1 Guide Interferometer Internal Metrology Error 23.73
  - 1.2.2 Difference Between Guide Starlight and Internal Metrology Beams 139.10
  - 1.2.3 Systematic Fringe Measurement Error 30.41
  - 1.2.4 Brightness Dependant Fringe Error 1.94
- 1.3 Science Interferometer 453.64
  - 1.3.1 Science Interferometer Internal Metrology Error 70.13
  - 1.2.2 Difference Between Guide Starlight and Internal Metrology Beams 273.38
  - 1.2.3 Systematic Fringe Measurement Error 30.41
  - 1.2.4 Brightness Dependant Fringe Error 353.53
- 1.4 Stellar Abberation 58.05
- 1.5 Colinearity Between Baselines 12.12



SIM Reference Design Performance
Narrow Angle

JPL

SIM Space Interferometry Mission

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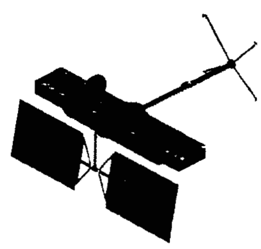
1 Hour Composite Accuracy (with baseline attitude error) 0.82 µas

- 1 Hour Composite Accuracy 36.61 pm 0.76 µas
  - 1.1 External Metrology 10.19
    - 1.1.1 Science External Metrology Error 2.91
    - 1.1.2 Guide External Metrology Error 2.60
    - 1.1.3 Tetrahedron External Metrology Error 22.89
    - 1.1.4 Absolute External Metrology Error 4.27
  - 1.2 Guide Interferometer 19.91
    - 1.2.1 Guide Interferometer Internal Metrology Error 3.67
    - 1.2.2 Difference Between Guide Starlight and Internal Metrology Beams 5.79
    - 1.2.3 Systematic Fringe Measurement Error 9.62
    - 1.2.4 Brightness Dependant Fringe Error 6.03
  - 1.3 Science Interferometer 28.19
    - 1.3.1 Science Interferometer Internal Metrology Error 6.52
    - 1.2.2 Difference Between Guide Starlight and Internal Metrology Beams 7.83
    - 1.2.3 Systematic Fringe Measurement Error 9.62
    - 1.2.4 Brightness Dependant Fringe Error 24.00
- Baseline Attitude Error 0.31 µas
  - 1.4 Stellar Abberation 3.88
  - 1.5 Colinearity Between Baselines 3.83



Dynamics and Control Test

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Space Interferometry Mission

SIM

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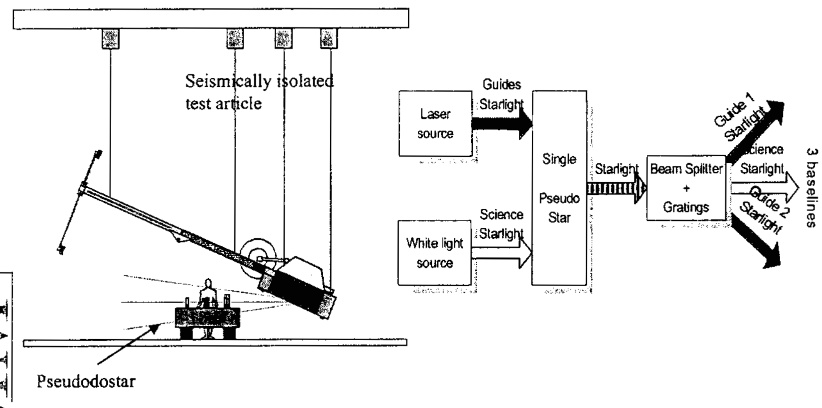

Picometer Performance Test

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Space Interferometry Mission

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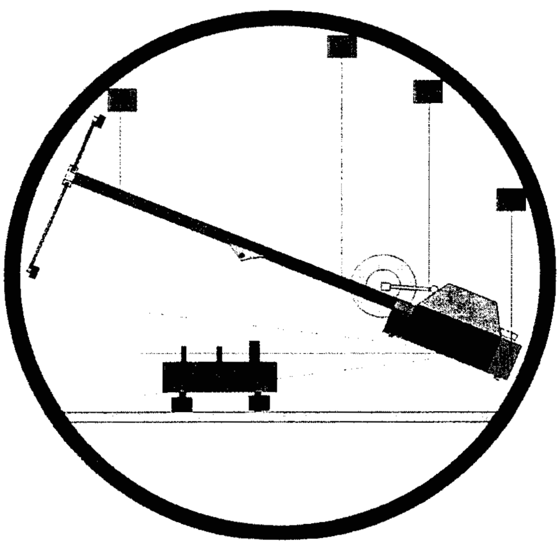

Test Planned for Lockheed Martin Delta Thermal Vacuum Chamber

Summary

JPL

Space Interferometry Mission

- Interferometers can image objects by making a series of measurements of the Fourier Transform of the target
- Interferometers can measure star positions very accurately by measuring the "position" of the central fringe
- High-performance auxiliary systems are needed to do this (pointing, pathlength control)

- The SIM reference design
  - includes capabilities for imaging and nulling
  - requires a complex external metrology system
  - requires significant deployments
  - has a significant amount of electronics

SIM

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Space Interferometry Mission

Backup Slides

SIM

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Moving from cartoon towards reality

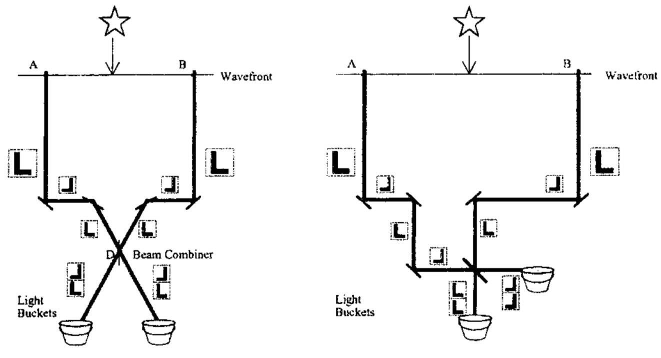


Image Rotation Problem!

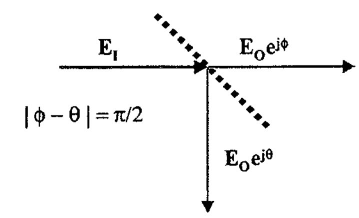
Image Rotation is fixed

SIM Space Interferometry Mission

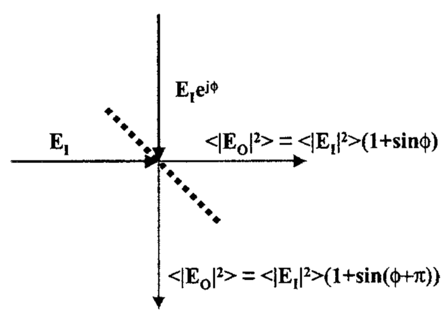
A NASA Origins Mission

How beamsplitters work

- A beamsplitter's outputs are out of phase from each other by 90 degrees, and from the input by 45 degrees.



- With two equal inputs at exactly equal path, the beamsplitter's outputs are equal.
- With a 90-degree phase shift between the inputs, a complete null/bright is achieved.



SIM Space Interferometry Mission

A NASA Origins Mission

Flight Subsystems

- Starlight (STL) Subsystem
  - Collects starlight and measures interferometer fringes
- Metrology (MET) Subsystem
  - Measures internal and external pathlengths
- Real Time Control (RTC) Subsystem
  - Provides computers and electronics to operate SIM
  - Performs all controls functions
- Precision Structure (PSS) Subsystem
  - Provides stable structure for interferometer components
  - Deployment mechanisms
- Spacecraft Subsystem
  - Provides standard spacecraft functions (e.g. ACS, telecom)

SIM Space Interferometry Mission

A NASA Origins Mission

SIM Starlight Subsystem Design Overview

- Collects starlight and interferes them and measures interferometer fringes
  - Acquires stars over a 15 degree field of regard and interferes them
  - Provides sensors and actuators for dynamics and control functions
- Equipment List
  - Siderostat Bay
    - Siderostat mirror and gimbal
    - Beam compressor
    - Fast Steering Mirror
    - Sid camera
  - Transport Optics
    - Turning mirrors
    - Switchyard
  - Delay Line
  - Beam Combiner
    - Angle and fringe tracking CCDs
    - Nuller

SIM Space Interferometry Mission

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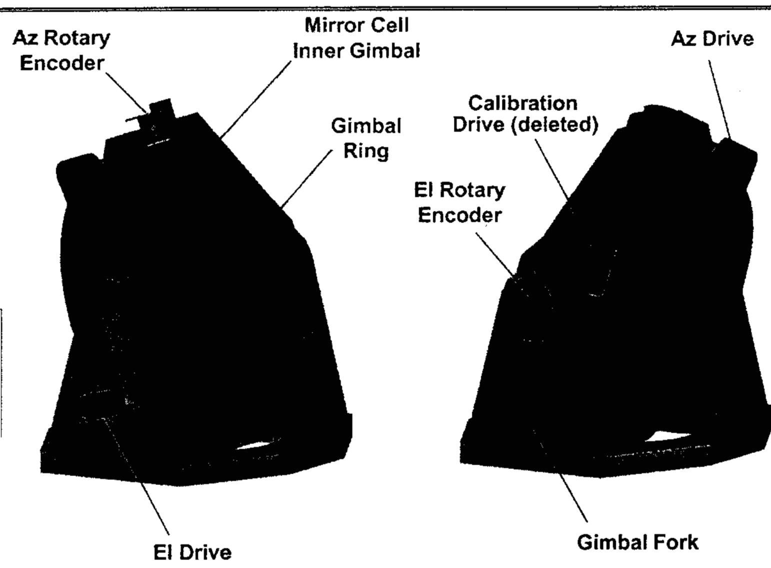
Siderostat Assembly

JPL



SIM Space Interferometry Mission

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SIM Metrology Subsystem Overview

JPL

- External metrology
  - External metrology measures
    - 2 guides and science baseline lengths
    - relative orientation between the three baselines
  - 4 vertices are used to triangulate on siderostat cc positions
    - 1 extra for redundancy and for calibration of corner cubes
  - Absolute metrology system is used to determine geometry of optical truss
- Internal metrology
  - Internal metrology measures starlight path from beam combiner to siderostat cc
    - critical that IM is parallel to starlight
- Equipment List
  - Metrology Source
    - Laser
    - Frequency shifters and modulators
    - Fiber distribution system
  - Beam Launchers
    - 34 external, 8 internal
  - Fiducials
    - 4 triple corner cubes
    - 11 single corner cubes - 7 siderostats, 4 beam combiners

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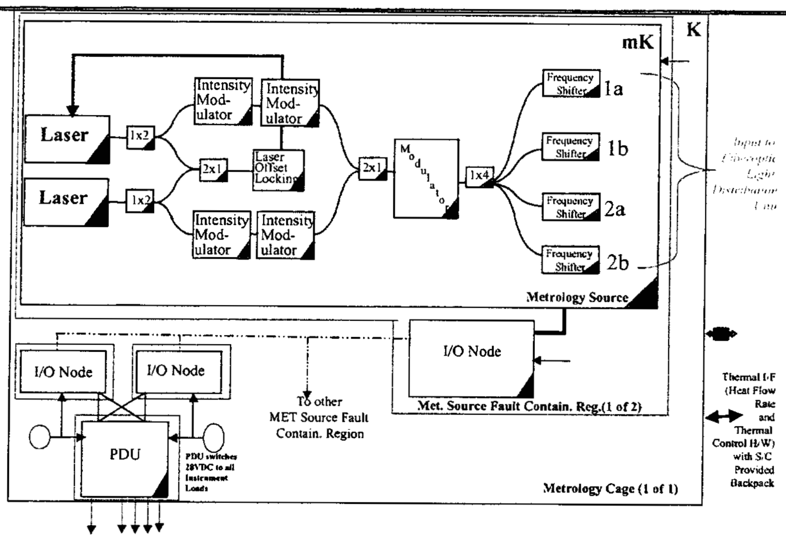
Metrology Subsystem Block Diagram

JPL

Space Interferometry Mission

SIM



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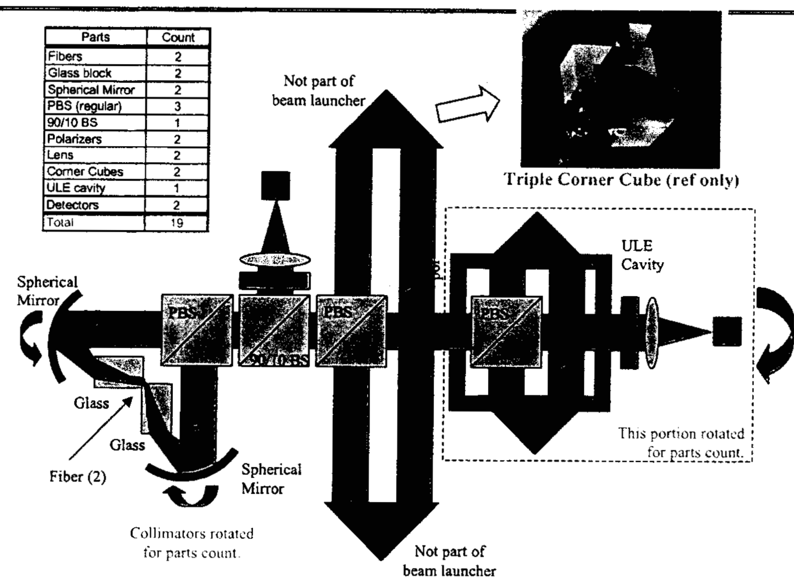
Metrology External Beam Launcher

JPL

Space Interferometry Mission

SIM

Parts	Count
Fibers	2
Glass block	2
Spherical Mirror	2
PBS (regular)	3
90/10 BS	1
Polarizers	2
Lens	2
Corner Cubes	2
ULE cavity	1
Detectors	2
Total	19



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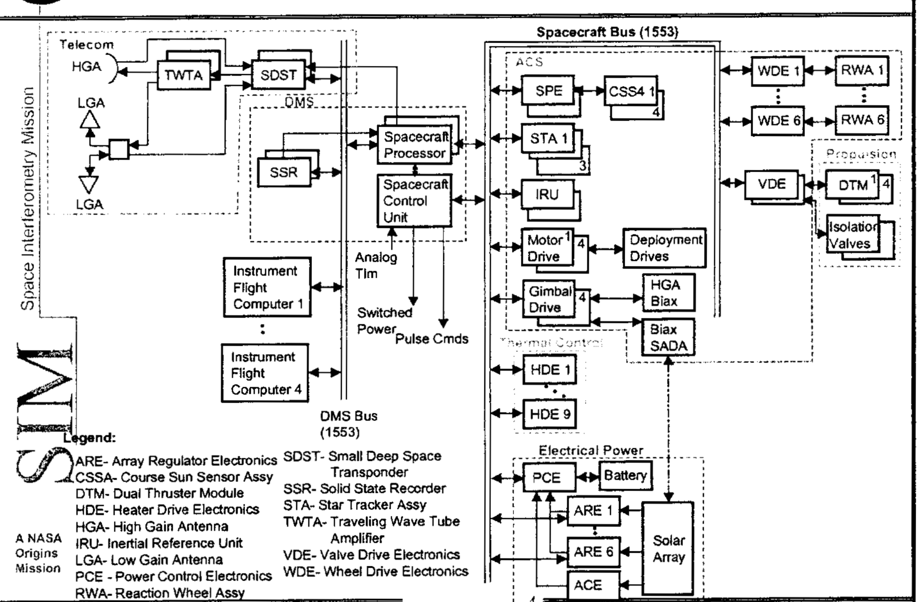
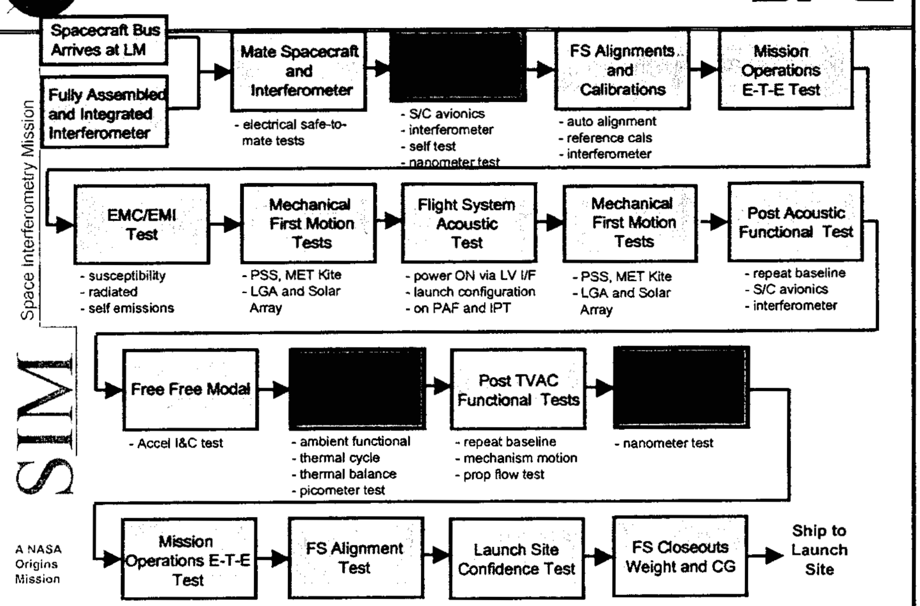
S/C Avionics Block Diagram



Assembly Test and Launch Operations



SIM Space Interferometry Mission

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External Review Board
Design Study Overview

Peter Kahn
Tiger Team Lead
Flight System Engineer

22 March 2001

SIM Space Interferometry Mission

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Introduction and Agenda

- Study Process
- Overview of Design Options
- Design Details
  - Shared Baseline SIM
  - ParaSIM
  - Sonata
- Design Comparisons
  - Science Throughput
  - Integration and Test
  - Calibration
  - Risk and Reliability
- Summary

Charge to the Team

- Develop one design concept that preserves as much of the SIM science as possible within the $930M cost cap
- Develop a second, minimum, planets only, design concept that will provide a cost substantially ($100M - $150M) below the cost cap
- Develop a third concept somewhere in between the first two
- Fully engage the SIM team (JPL, ISC, Lockheed Martin, TRW, and the SIM Science Team) in the design study activity
- Assume a shuttle launch with an upper stage
- Capitalize on recent beam launcher technology development to reduce cost and risk
- Work closely with the IA to develop an accurate system baseline for the Independent Cost Estimate
- Be ready for the Code S reviews in March and April

SIM Space Interferometry Mission

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Mission Concept Study Process

- Reduce Mission Scope
  - Relax Level 1 Science Requirements
    - Provides some flexibility in Error Budget allocations
  - Eliminate Wide Angle capability (including Grid) if possible
    - Relaxes requirements on Field of View coverage
    - Reduces pre-launch science activities
    - Reduces Science Center processing (Grid)
- Trade the complexity in one subsystem for simplification in another
- Reduce parts counts
  - Front end optics
  - Metrology Components
- Other Focus areas
  - Shuttle launch
  - Schedule and I & T optimization

SIM Space Interferometry Mission

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Design / Risk Simplifications

SIM Space Interferometry Mission

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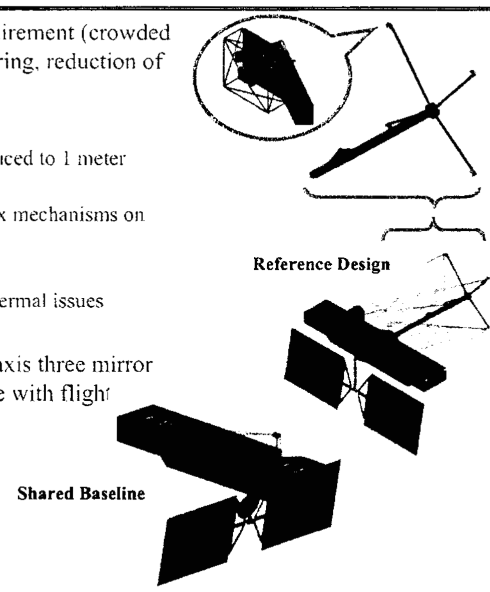
- Removing imaging science requirement (crowded field astrometry) allowed clustering, reduction of siderostats
  - External Metrology
    - 9 meter boom and kite reduced to 1 meter boom
    - No electronics and complex mechanisms on boom/kite
    - No complex deployment
    - Minimum dynamics and thermal issues
    - Beams reduced by ~50%
  - Introduced a simplified on-axis three mirror anastigmat (TMA) telescope with flight heritage



Design / Risk Simplifications (cont'd)

SIM Space Interferometry Mission

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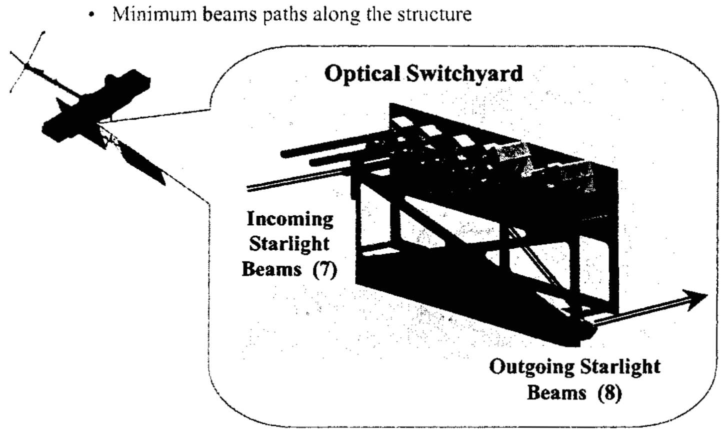
- Removing imaging science requirement (continued)
  - Deleted Switchyard
    - Reduces optical complexity and risk
    - Minimum beams paths along the structure



Design / Risk Simplifications (cont'd)

SIM Space Interferometry Mission

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- Removing nulling demonstration requirements
  - Deleted extra nulling beam combiner
  - Deleted optical switch to insert beam combiner in path
- Shuttle launch removed volume constraints
  - Single monolithic structure simplifies optical bench construction
  - No deployment of the 11 meter precision structure (PSS)
  - Eliminates microdynamics concerns/uncertainties across PSS hinges and latches
  - Increased volume allowed flexibility in design options
    - Volume margin can be traded against other resources in the future
- Reduced mechanism count, and associated electronics and software, about 50%
- New, highly simplified beam launcher now in development has potential for reducing cost, risk and Implementation Phase schedule
- Schedule and I&T optimization based on new designs studied
- Tiger team approach coupled with ideas provided from outside the SIM team (IA & SIMTAC) enabled a fresh look at options
  - Carrying three options enabled very positive cross pollination of designs

Need for a Grid

SIM Space Interferometry Mission

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- Grid plays a significant role in External Calibration of the instrument and understanding of instrument performance
  - Grid provides for finding and eliminating systematic errors
  - Operations Phase risk reduction
  - Enables search for long period planets
    - Without grid, unknown proper motion of reference stars causes results in false acceleration of target star
    - as large as 4 ~ 10 uas over a 5 year mission
    - The SIM grid (accurate to 4 uas in position and 2 uas/year in proper motion) is more than adequate to eliminate false acceleration
- But Sonata cannot make its own grid.

Commonality of All Designs

JPL

SIM Space Interferometry Mission

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- SIM builds on years of interferometry design and technology investment
  - Several years spent on Reference Design
  - A year spent on detailed conceptual design of alternative concept called SOS
  - Other interferometers (Keck, Palomar, etc.)
- All SIM Interferometer design variations contain common elements
  - Management/Outreach/System Engineering
  - Mission Systems
  - ISC Core
  - Backend optical trains are mostly identical
    - Variations only in quantities(e.g. Delay Lines, Beam Combiners, etc.)
  - Very minor differences in Precision Structures
  - Spacecraft is very similar for all designs
    - Some variations in ACS performance and stability
- Identified discriminators largely in:
  - External Metrology
  - Front-end optics
  - Pointing Mechanisms
  - Front-end Sensors
  - Software (Flight and ISC science processing)

Mission Concept Options

JPL

SIM Space Interferometry Mission

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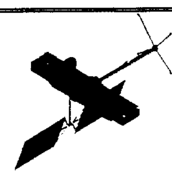
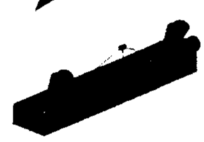
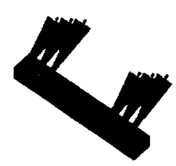
- Reference Design (SIM Classic)
  - This is the design which was reviewed by the IA team
  - Project and IA costs based on this design



- Shared Baseline SIM
  - Over 90% of Reference Design science capability
  - Shared front-end optics
  - Reduces external metrology from 36 to 18 beams
  - Greatly simplified metrology boom; ~50 fewer mechanism:

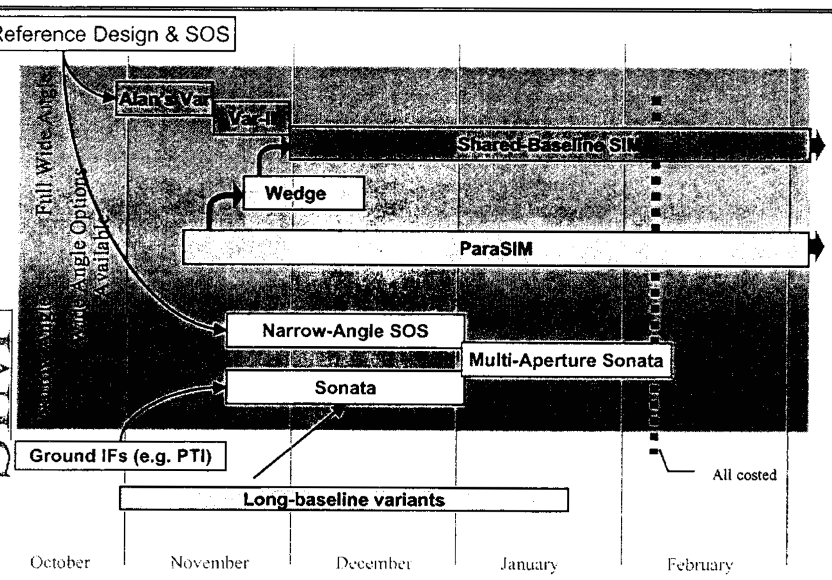


- ParaSIM
  - Same astrometric accuracy as Shared Baseline
  - Reduced science throughput: 30% to 50% of Reference Design
  - 1 less interferometer than Shared Baseline SIM
  - Reduces external metrology beams from 36 to 10; no boom



- Sonata
  - Planet finding only, no Grid
  - Provides only about 20% of Reference Design science
  - Reduces external metrology beams from 36 to 2; no boom
    - Simplest metrology of all options

Design Evolution



SIM Space Interferometry Mission

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Design Details

SIM Space Interferometry Mission

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Shared Baseline SIM

Space Interferometry Mission

SIM

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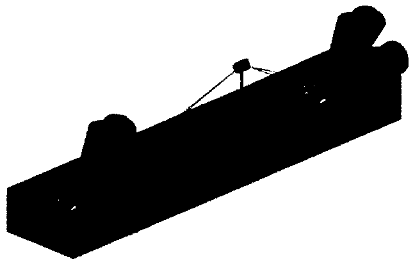

- **Engineering Delta**
  - Greatly reduces external metrology boom complexity, and reduces number of beams from 36 to 18
  - Two Baselines, one shared by two Guide Interferometers and one shared by two Science Interferometers
  - Two interferometers on a single baseline share siderostat mirrors and use wide field-of-view of TMA (Three-Mirror Anastigmat) telescopes

- **Description**
  - Combines the best of Reference Design and SIM-SOS into a lower cost design
  - Most similar to Reference Design
    - Best understood of the options
    - Best performance of the options
  - Best redundancy capability
  - Provides degraded mode option

- **Science Capability**
  - Retains Level 1 planet finding req'ts
  - Retains capability to do the Grid
  - Retains Level 1 global astrometry capability requirements
  - Imaging Demonstration capability
    - Limited U,V point ring
  - No nulling capability

Shared Baseline SIM

Space Interferometry Mission

SIM

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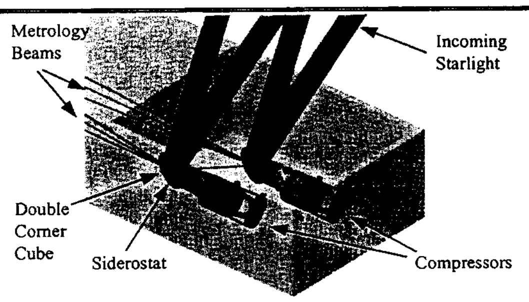
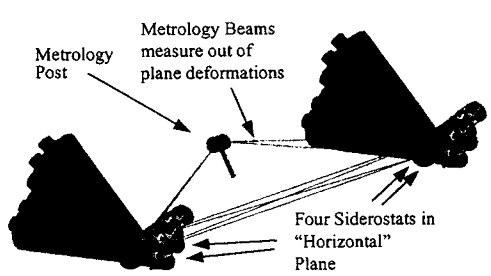




Major Components	Shared Baseline
Siderostats	4
Siderostat FOR	15 Deg (+/-7.5) w/PZT 2nd stage
Number of Front end Cameras/sensors	One Camera/Sid; 4 IR quad Cells
CC s and Type	5; 4 Double & 1 Single
Siderostat xlation Mechanisms	2 DOF on one Pallet
Telescopes and Type	8; on-axis TMA
Number of Baselines	2
Number of simultaniously operating Interferometers	3
Number and type of External Metrology Beam Launchers	18; RT or V-V w/Dither
FSMs	8
Internal Beam Launchers	4; SAVV
Number & Length of Delay Lines	8; 4 2-Stage; 4 1-stage; 1.5m
Number of Lasers	3
ABCs	4

Shared Baseline SIM
Simplifications From Reference Design

JPL

SIM Space Interferometry Mission — A NASA Origins Mission

- Sharing Siderostats
  - 4 Siderostats versus 7 for Reference Design
- Common design of Guide and Science optics
  - Simplified On-axis TMA design vs. off-axis confocal paraboloids for Reference Design
- Direct baseline measurement instead of complex Optical truss
- External Metrology Simplified Significantly
  - Metrology Post is 1 m versus 9 m plus kite for Reference Design
  - No Beam Launchers on Met Post
  - No Metrology Electronics or Thermal Control hardware
  - Far Fewer Metrology Beams required
- Graceful Degradation in event of certain failures
  - Best redundancy capability

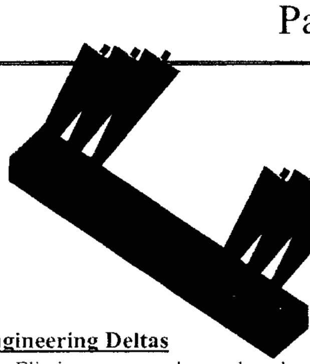
PROS:
- Most like Reference Design
- Maintains maximum science
- Has graceful degradation paths to ParaSIM

CONS:
- Highest cost of three options
- Most metrology

ParaSIM

JPL

SIM Space Interferometry Mission — A NASA Origins Mission

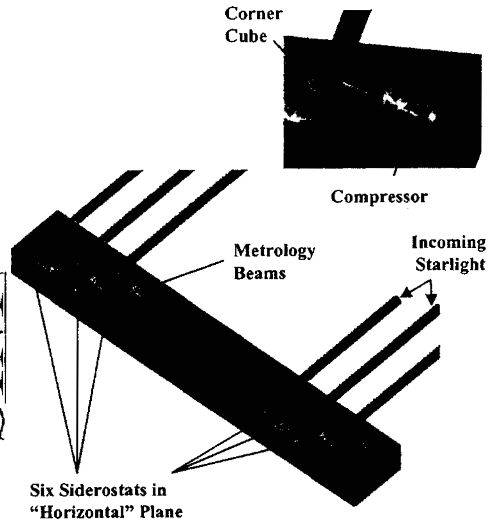


- **Engineering Deltas**
  - Eliminates external metrology boom, and reduces number of beams from 36 to less than 10
  - Only three interferometers (third is for redundancy)
  - Simplified telescope design
  - Requires substantially more spacecraft positioning
    - Baseline to be in line with the guide and science stars for each measurement
    - Requires multiple guide stars for each science star

- **Description**
  - New concept for performing SIM science
  - Measures arc length between reference stars and target stars
  - Look for periodic motion of star relative to nearby stars

- **Science Capability**
  - Can do same astrometry as Reference Design, but with fewer science targets
    - Retains planet finding capability
    - Capable of doing Grid and global astrometry
  - Imaging demonstration capability more limited than Shared Baseline
  - No nulling capability

ParaSIM



Major Components	ParaSIM
Siderostats	6
Siderostat FOR	15 Deg (+/- 7.5 deg) w/PZT 2nd stage
Number of Front end Cameras/sensors	4 IR quad Cells
CC s and Type	4; 3 Double & 1 single
Siderostat xlation Mechanisms	2 DOF on one Pallet
Telescopes and Type	4; On-axis; 2-mirror
Number of Baselines	3
Number of simultaniously operating Interferometers	2
Number and type of External Metrology Beam Launchers	10; RT or V-V w/Dither
FSMs	6
Internal Beam Launchers	3; SAVV
Number & Length of Delay Lines	3; 3-stage; 8cm
Number of Lasers	3
ABCs	3

ParaSIM
Simplifications From Reference Design

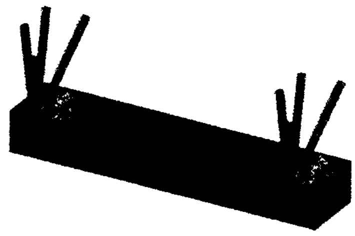
- Fewer Siderostats
  - 6 Siderostats versus 7 for Reference Design
- Fewer Telescopes
  - Simplified (On-Axis) common design of Guide and Science optics (TMAs)
- Eliminated one interferometer
- Direct baseline measurement instead of complex Optical truss
- Eliminated many mechanisms
- External Metrology Simplified Significantly
  - No Metrology Boom or associated electronics and Launchers
  - Far Fewer Metrology Beams required

PROS:
- Grid capable
- Easiest external calibration

CONS:
- Observationally inefficient
- Stresses ACS - lots of turns
- Requires tighter ACS Control

Sonata

SIM Space Interferometry Mission

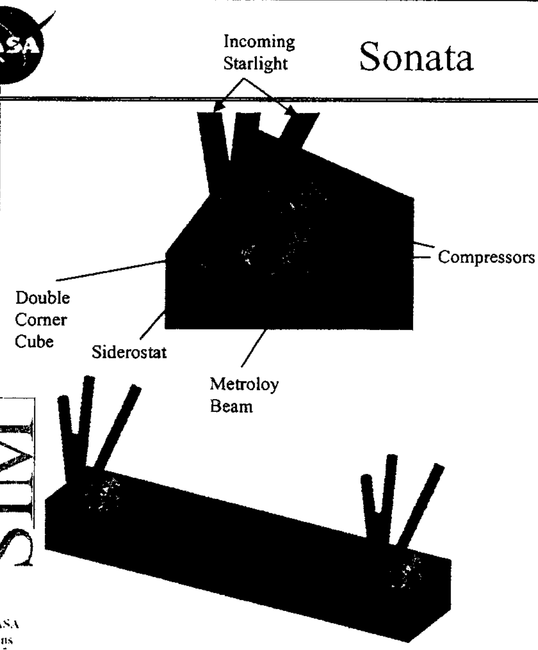


- **Description**
  - Concept influenced by ground-based design (viz Palomar Testbed Interferometer and Keck Interferometer)
  - Limited to a narrow field of regard
- **Science Capability**
  - Degraded planet finding capability only
    - Same accuracy as Reference Design but cannot detect planets with periods greater than the mission lifetime
  - No Grid capability
  - No global astrometry capability
  - Very Limited Imaging Demonstration capability
  - No nulling capability
- **Engineering Deltas**
  - Simplest external metrology system with a reduction of beams from 36 to 2
  - Simplified front-end optics
  - Four interferometers share one common siderostat mirror and use TMA (Three-Mirror Anastigmat) telescopes to select 2 guide and 1 science stars

A NASA Origins Mission

Sonata

SIM Space Interferometry Mission



Major Components	Sonata
Siderostats	2
Siderostat FOR	1 Deg (+/- 0.5 deg) w/PZT 2nd stage
Number of Front end Cameras/sensors	tbd
CC s and Type	2; One Double, 1 Single
Siderostat xlation Mechanisms	N/A
Telescopes and Type	8; on-axis TMA (Conic)
Number of Baselines	1
Number of simultaniously operating Interferometers	3
Number and type of External Metrology Beam Launchers	2;Old Style w/Dither
FSMs	8
Internal Beam Launchers	4; SAVV
Number & Length of Delay Lines	4; 3-stage; 8cm
Number of Lasers	2
ABCs	4

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Sonata
Simplifications from Reference Design

- Fewer Siderostats
  - 2 Siderostats versus 7 for Reference Design
- Common design of Guide and Science optics
  - On-axis three-mirror anastigmat (TMA) vs off-axis confocal paraboloids for Reference Design
- 1 Baseline & 3 Interferometers (the 4th is redundant)
- Direct measurement of baseline length
- External Metrology Simplified Significantly
  - No Metrology Boom or associated electronics and Launchers
  - Only 1 External Metrology beam required

PROS:
- Lowest cost

CONS:
- Only Narrow Angle Science
- No Grid capability
- Analysis of FAM to reduce beamwalk is TBD
- Least heritage
- Greatest cost and technical risk

SIM Space Interferometry Mission
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Design Comparisons

SIM Space Interferometry Mission
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Science Throughput Comparison

Mission Type	Accuracy	Shared Baseline		ParaSIM (with CMGs)		ParaSIM (with RWAs)	
		# Targets	% of Mission	# Targets	% of Mission	# Targets	% of Mission
Deep Search	1 µas	250	17.5	250	22.5	250	41.2
Broad Survey	4 µas	2000	9.5	1570	47.5	540	28.8
Wide Angle	10 µas	31800 Bright (m=16) *OR* 4390 Dim (m=19)	43	0	0	0	0
Cost		**$927 M**		**$927 M**		**$906 M**	

Note: 30% of mission time is allocated for Grid and calibration

SIM Space Interferometry Mission
A NASA Origins Mission

Testability

- I&T Flow/Configuration Evaluation
  - Baseline integration flows are evaluated for each of the three configurations relative to:
    - whether new test types are required or whether tests can be eliminated or combined
    - task complexity(risk) changes
    - integration additions and deletions
  - I&T schedules are created and compared for each configuration
    - Include subsystem I&T duration, Interferometer I&T and ATLO duration
  - Subsystems are fully verified prior to start of Interferometer I&T for all configuration options
    - "Starlight" subsystem kept as critical path driver prior to II&T start
  - Evaluation performed for Shared Baseline, ParaSIM, and Sonata
    - detailed schedules built for ParaSIM and Shared Baseline configurations
- Two-baseline system test of Flight System
  - Reference Design only had a single baseline test
  - Results in better test of Flight System

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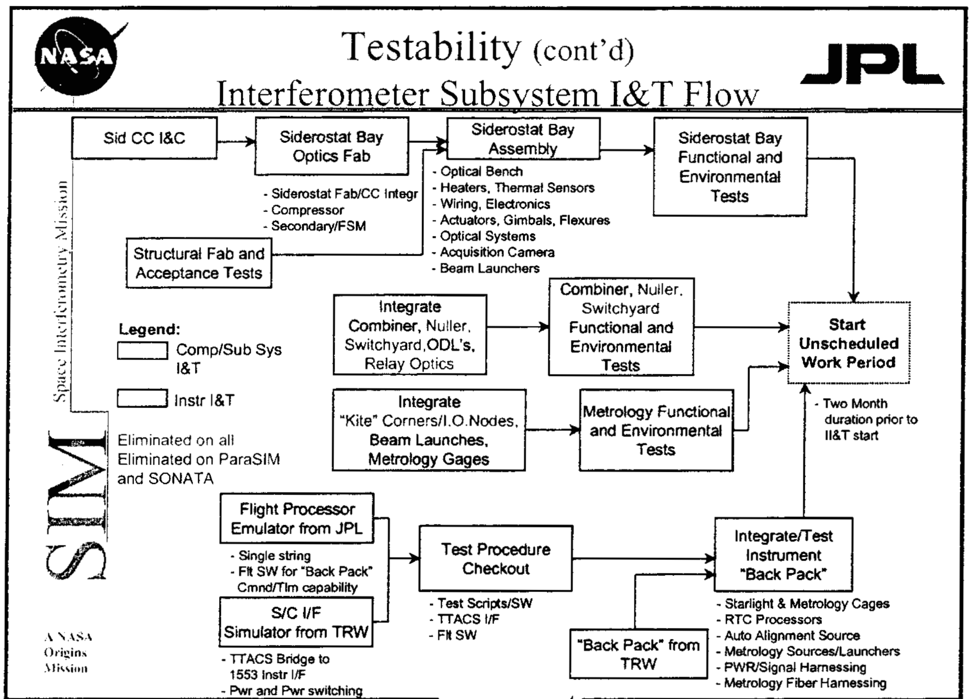
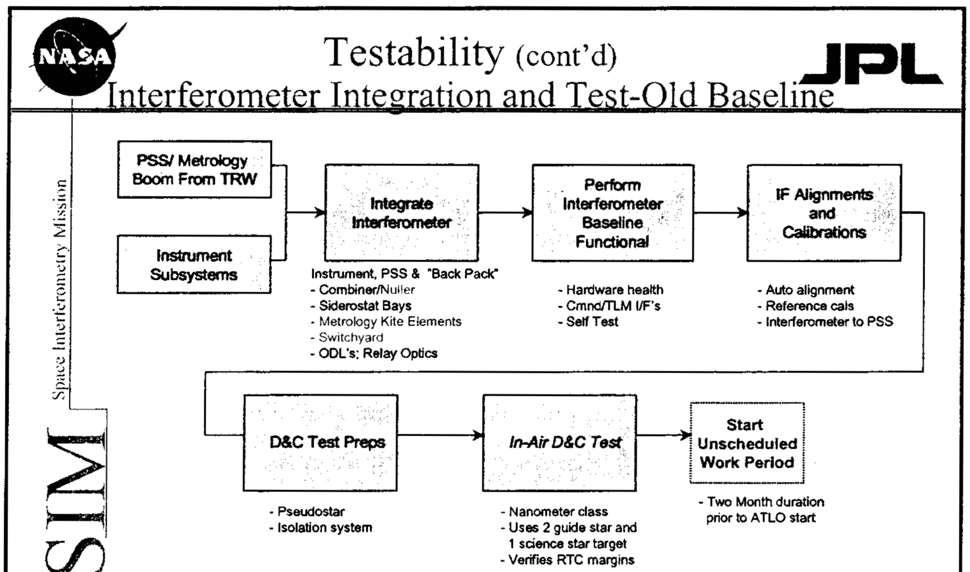
Testability (cont'd)

Interferometer Subsystem I&T Flow



Testability (cont'd)

Interferometer Integration and Test-Old Baseline



Legend:
- Metrology Boom on Shared Baseline Only
- Eliminated on all Configurations
- *Candidate for combining with Astrometric vacuum test phase*

Testability (cont'd)
Summary/Conclusions

JPL

Space Interferometry Mission — SIM — A NASA Origins Mission

- No discernible schedule discriminators among the three designs
  - redundancy approach resulting in similar numbers of "starlight subsystem" hardware elements for all options
  - all configurations have improved TVAC chamber compatibility due to boom elimination or reduction
- Schedule reduction of 41 working days
  - main advantage over old baseline is if D&C and Astrometric testing can be accomplished with one setup and pseudostar type
- Pseudostar development remains challenging
- Shared Baseline and ParaSIM very similar
  - External metrology comparable to additional siderostats
- Sonata much the same except for more complex pseudostar interface for D&C testing
  - Haven't figured out how to test Sonata
- Two-baseline system test of Flight System instead of single baseline test

Calibration
The Need for Calibration

JPL

Space Interferometry Mission — SIM — A NASA Origins Mission

- SIM is not an ideal interferometer.
  - Diffraction: difference in path between starlight, metrology, and a ray passing through the system.
  - Polarization: mostly in metrology, false pathlength reading due to polarization changes as corner cubes articulate
  - Beam Walk: tilt of siderostats, dihedral errors on rotating corner cubes
  - Time-dependent terms: beam walk, changing optical figure, other.
    - These are specified in the error budget to remain below some tolerable level.
  - Two types of calibration analyzed:
    - External (stellar references and the Grid)
    - Internal (using an internal source)

Calibration (cont'd)
Current Calibration Status

Space Interferometry Mission

SIM

- External Calibration
  - Shared Baseline: current concept showspromising first results
    - 10 uas measurements lead to 10 uas calibration accuracy.
    - Current scheme may take half-day on orbit. But likely we will see 6 hours or less required.
  - ParaSIM: initial proof of concept complete
    - We understand how to do it, how well it works, multipliers, etc. (Assuming the physics models are reasonably representative of the smoothness of the effects.)
    - Can calibrate wide and narrow angle to about 10 and 1 uas, respectively.
  - SONATA
    - No scheme has been identified for external calibration with SONATA

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Calibration (cont'd)
Current Calibration Status (cont'd)

Space Interferometry Mission

SIM

- Internal Calibration:
  - Has the potential to improve overall performance by as much as 40% end-to-end compared to external calibration.
  - Potentially works for both ParaSIM and Shared Baseline.
  - Internal calibration is not a performance discriminator between the two designs.
  - Technique and sensitivities are somewhat different for SONATA.
- Concepts for internal calibration exist on paper.
  - Analysis is proceeding.
- Sensitivities to various sources of error are being studied.
- Impacts to testbeds are being studied.

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Risk and Reliability

Space Interferometry Mission

SIM

A NASA Origins Mission

- No Single Point Failure allowed
- Block redundancy has been assumed for costing studies
  - "Blocks" are at highest level (e.g., interferometer)
  - Other functional. reliability approaches will be investigated
- Ultimately a standard Risk Management Approach will be applied to the selected design

Risk and Reliability (cont'd)

Space Interferometry Mission

SIM

A NASA Origins Mission

- Features that reduce risk
  - Monolithic Structure for all designs
    - Eliminates Deployment concerns
    - Eliminates microdynamics concerns with hinges and latches
  - External Metrology reduction for all designs
    - Significantly reduces complexity by eliminating Metrology Kite
      - Beam launchers, mK Thermal, Deployments, Mechanisms, etc.
    - Boom Simplified (Shared Baseline)
      - 1 meter *vs.* 9 meter with 4 arms
      - Single deployment
    - Boom eliminated (ParaSIM and Sonata)
  - Simplified Optics
    - On-axis TMA design with Flight heritage
    - Fewer Siderostats
  - Overall significant reduction in mechanisms (~ 50%)
  - On-Orbit Graceful Degradation
  - Shuttle Launch

Risk and Reliability (cont'd)

- Features that add risk:
  - Shared Baseline
    - Shared Siderostats
    - Front-Back Double Corner Cube
  - ParaSIM
    - Front-Back Double Corner Cubes
  - Sonata
    - FAM "Chopping" Technique
    - Shared Siderostats

SIM Space Interferometry Mission

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Testability, Calibration, and Risk/Reliability Comparison

	Shared Baseline	ParaSIM	Sonata
Testability	o Schedules similar + Potential two-baseline system test	o Schedules similar + Potential two-baseline system test	o Schedules similar – More complex pseudostar interface for D&C
Calibration	+ External: promising o Internal: good potential; not a discriminator	+ External: initial proof of concept exists o Internal: good potential; not a discriminator	– External: no scheme identified o Internal: somewhat different; not a discriminator
Risk / Reliability	+ Possible degraded mode: ParaSIM	+ Boom eliminated – New concept: baseline planarity	+ Boom eliminated – New concept: chopping FAM

Note: comparison is among the three new options. Comparison with Reference Design would show more discriminators.

SIM Space Interferometry Mission

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Summary

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SIM Space Interferometry Mission

- Three designs were studied
  - Variations and options within those designs were further studied
  - The designs (Shared Baseline, ParaSIM and Sonata) were costed
  - Risk, reliability, Testability and Calibration were part of the Trade
- Science Impacts, inputs and support were supplied by the SIM Science Team
- A detailed, formal design evaluation process was followed
- Team recommended Shared Baseline to Project Management

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Summary of Key Questions

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SIM Space Interferometry Mission

1. Where does SIM fit in the larger framework of other missions and other techniques?
   - SIM does unique science that no other planned mission can/will do
   - SIM is necessary for TPF (technology and target identification)
2. Is SIM feasible from an engineering and technology perspective? ***YES***
   - **The redesigned SIM mission is not more complex than missions that have successfully flown (per the SIMTAC)**
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap? ***YES***
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets? ***NO***
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry? ***YES***
   - This capability allows SIM to detect long-period (>5 year) planets required to identify solar system analogs for TPF

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SIM Space Interferometry Mission

Space Interferometry Mission (SIM) Science Comparison

Michael Shao
SIM Project Scientist

March 22 2001

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Outline

JPL

SIM Space Interferometry Mission

- 3 Rescoped Options
  - How they are different (scientifically)
    - Astrometric observations
    - Science throughput
  - Science team consensus recommendation
- Science with the rescoped SIM
  - Planets
    - Deep survey for planets
    - Broad survey for planets
  - Astrophysics
    - Galactic
    - Extra galactic
- Summary

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Mission Concept Options

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SIM Space Interferometry Mission

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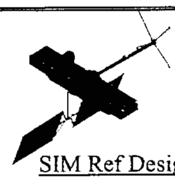
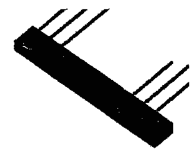
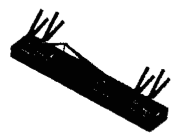


SIM Ref Design
- Highest science output
- Includes imaging/nulling
- Best planet search throughput



PARASIM
- **Can do complete Deep Search, and partial Broad Survey for TPF targets**
- Can do global astrometry at low throughput



SHARED BASELINE
- **Can do complete Deep Search and Broad Survey of TPF Targets**
- Can do global astrometry, with little loss from Ref design

SONATA
- Derived from Keck Architecture
- **Complete Deep Search and Broad Survey for TPF targets, contingent upon FAME**
- Can not do global astrometry

Astrometry with an Interferometer

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SIM Space Interferometry Mission

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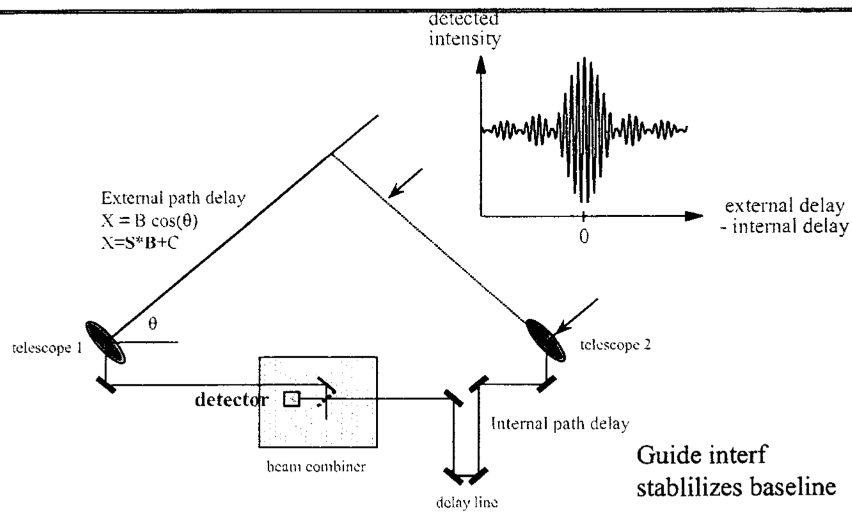
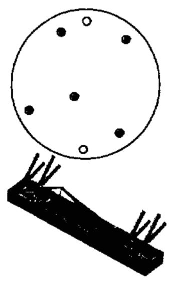


The peak of the interference pattern occurs when the internal path delay equals the external path delay

Guide Stars, Grid Stars, Ref Stars



- Guide stars are used to "stabilize" the spacecraft attitude
  - Guide stars are bright 7~8 mag stars, need 2 guide stars per 15 deg diameter tile

    Active control to sub arcsec, motion knowledge to uas
- Grid stars are ~12 mag stars (K giants) that are observed repeatedly over the mission, whose positions will be known to ~ 4uas (pm 2 uas/ur)

  Grid stars are used to determine the baseline vector @ uas's

  Absolute orientation of baseline to uas
- Reference stars are for narrow angle (planets) only. At 1uas, the grid stars are not known to be stable. We've adopted the approach of using many (4 per degree of freedom) ref stars so that we can identify what ref stars have no companions. (4 was picked so that we would end up with 2)

SIM Space Interferometry Mission

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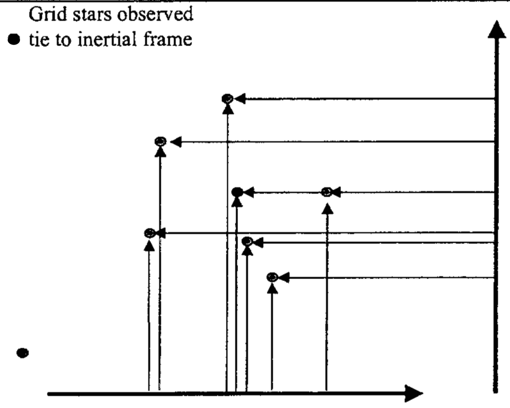
How SIM Makes Astrometric Measurements

Grid stars observed

● tie to inertial frame



Repeat with baseline ~ 90 deg rotated

30 sec integration

15 sec delayline slew to next

What we measure:

Position of target wrt the average position of the reference stars

Position of the ref stars wrt each other.

Guide interferometer locked on guide stars

Science interferometer switches between target and ref stars.

30 sec integration on target, 30 sec ref star

T-R1-T-R2-T-R3-T-R4-T-R5, repeat once

Chop between ref/target to reduce thermal drift effects.

SIM Space Interferometry Mission

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Parasim Measurements

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SIM Space Interferometry Mission

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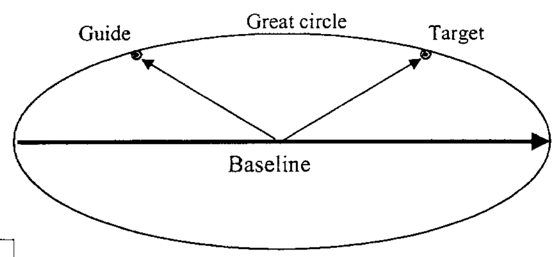

Key differences			
	# Interferometers	Constraints	Measures
PARASIM	2	In Plane	arcs
All Others	3	None	projections
PARASIM needs a spacecraft manuever for every new Target			

Astrometric Measurements with Parasim

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SIM Space Interferometry Mission

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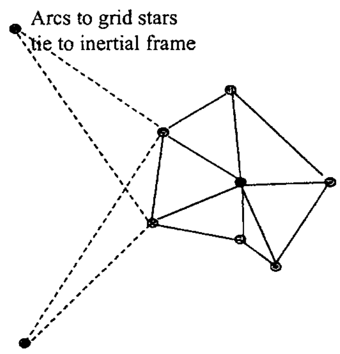


- Parasim measures the arc between two stars.
- **Target-reference arc for 8 reference stars**
- **8 Reference-reference arcs**
- **Two spacecraft slews for every reference star**

- Compared to shared baseline:
  - Spacecraft slews replace siderostat and delay line slews
  - Characterization of ref star accelerations requires arcs between reference stars; no overhead with shared baseline

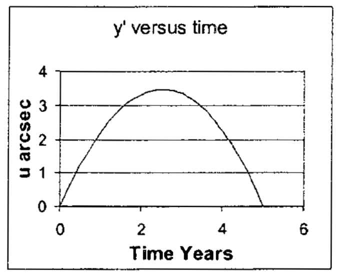
We do not expect SIM to be mechanically stable at the picometer level over hours. We do even expect the metrology to be stable to 10's picometers over a period of hours. If we make differential measurements on a fast enough time scale, we do expect those differential measurements to be accurate at the 10's picometer level.

The Need for a "Grid" in a Planet Search

Space Interferometry Mission — SIM

- Unknown proper motion of the reference stars causes a **rotation** of reference frame
- Results in **false acceleration of target star**
- Effect is due to frame rotation combined with target proper motion (see panel below)
- This effect can be as large as 4 ~ 10 uas over a 5 year mission
- Affects detection of **long period planets**

If proper motion of ref stars is known to 1mas/year, and the target star moves at 1 as/year, then target star <u>**appears**</u> to have 4 uas of non-linear motion



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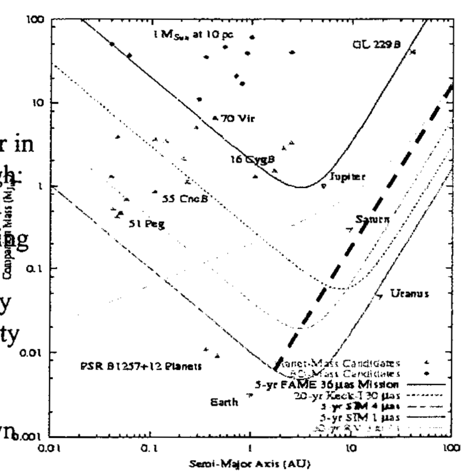
SIM Needs a Grid to Eliminate False Acceleration

Space Interferometry Mission — SIM

- The SIM grid (accurate to 4 uas in position and 2 uas/year in proper motion) is more than adequate to eliminate false acceleration
- A FAME accuracy grid (50 uas/year in proper motion) is almost good enough: false acceleration from a FAME grid would only degrade SIM planet finding result by a factor of sqrt(2) to 2
- A Hipparcos accuracy grid is grossly inadequate (20~40x) loss in sensitivity over a SIM-grid.
- One of the options (**SONATA**) is narrow angle only, can't make its own grid.



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SIM Planet Search Program

Space Interferometry Mission

SIM

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- Three key projects were awarded time on SIM to search for planets around nearby stars
  - One major part of the planet search program is the search for 3~5 Earth mass planets in the habitable zone around the **~250** A, F, G, K and M stars within 10 parsecs. **Deep Search** for beach front property.
  - A second equally important program was to conduct a **Broad Survey of 2000 Stars** within 20 pc that would place our own solar system in the context of planets in our part of the galaxy. The targets are planets with 10 Earth masses in the habitable zone, Jupiters around stars 500 pc away, planets around stars with different metallicity, age, mass, population.
  - A third equally important part of the planet search program is to look for Jupiter and Saturn mass planets in young stellar systems. Are planets formed then swallowed up? Are they formed and ejected? What is the origin of the planets we find in the Broad Survey? What does the presence of multiple Jupiters in young systems say about the existence of Earth mass planets in a mature planetary system? This is the **Young Stars** Planets Program.

TPF Targets

Space Interferometry Mission

SIM

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- NASA has directed that SIM is to provide a target list for TPF
- With 3 uas narrow-angle accuracy, SIM can perform a near complete survey of stars within 20 pc for:
  - terrestrial planets down to 15 earth masses in habitable zone
  - Planetary systems with massive outer planets that permit Earths in their habitable zones
- With narrow-angle accuracy of 1 uas, SIM surveys all single A, F, G, K and most M stars within 10 pc for terrestrial planets down to 3 earth masses

TPF-Centric SIM

- **Deep Search:** earthlike planets within 10 pc
  - there are ~250 targets reachable by TPF
  - narrow angle accuracy of 1 uas
- **Broad Survey:** solar system analogs within 20 pc
  - there are ~2000 targets reachable by TPF
  - narrow angle accuracy of 4 uas
- Priorities for a TPF-centric SIM mission
  1. Complete Deep Search (if 1 uas is achieved)
  2. Complete Broad Survey (or as much of it as possible)
  3. Pursue astrophysics science programs

SIM Space Interferometry Mission
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Science Comparison, Allocated Time

- Background
  - As part of the first SIM science AO the following assumptions were made
  - The planet search program in SIM is the most important single science program. There are 3 key projects aimed at studying planets around stars outside our solar system.
  - Since the release of the AO, the project has found that the 20% set aside for the grid is conservative and potentially could be cut by a significant amount. However for comparison between SIM options we've kept these assumptions.

Time allocation for SIM		
Grid		20%
Calibration		10%
1st AO		35%
	TPF Planets	10%
	Other NA	10%
	Global Ast	15%
Subsequent AO's		35%

- 35% of SIM time is not yet allocated

SIM Space Interferometry Mission
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TPF Throughput Comparison

Science Performance Summary		Number of targets and time percentage for a 5 year SIM mission							
Observing Program	Accuracy	Shared Baseline	%	ParaSIM	%	ParaSIM with CMG's **	%	SONATA	%
Deep Search	1 uas	250	17.5	250	41.2	250	22.5	250	24.1
Broad Survey	4 uas	2000	9.5	540	28.8	1570	47.5	1900	45.9
Wide Angle: Bright or Faint	10 uas	31800 or 4390	43.0	0+	0.0	0+	0.0	*****	

** CMG (control moment Gyroes ~120 times more torque than the wheels used in the other design options, for comparison only

Time already allocated to Deep Search and Broad Survey is 10%, 4% to young planets time for TPF targets must be significantly expanded

30% of SIM time currently book kept for the Grid and calibration (conservative)

Only Shared Baseline has the throughput to complete both the Deep Search and Broad Survey and have any time left over for astrophysics.

SIM Space Interferometry Mission

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Science Team

- **The SIM science team unanimously favors SBL design.**
- "After evaluating all three of the proposed designs, the Science Team concluds that the Shared Baseline (SBL) version of SIM preserved nearly all of the astrometric goals of the original SIM, at a substantially reduced cost. SBL offers the most efficient design for planet searches by increasing the number of target stars explored by a factor of 3-10 over the other two design options. Further, SBL's well understood ability to make wide angle observations accomplishes two additional important goals:"
  - (1) enables searches for planets with periods long compared to SIM's lifetime (i.e. planets well beyond the orbit of Jupiter) by establishing an absolute reference frame against which to measure small accelerations
  - (2) enables the wide variety of general astrophysics observations that made SIM a high priority mission in two NAS/NRC decadal reviews.
  - Because the project was unable to identify any inexpensive, planet-finding-only mission, and because the spread in estimated costs for the three designs is small relative to the uncertainties, the SIM Science Team unanimously favored the SBL design.

Shared baseline can't do
- Full uv-plane imaging
- Nulling
- Slight decrease in throughput for planets (wrt Classic)

SIM Space Interferometry Mission

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Five Key Questions

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SIM Space Interferometry Mission

1. Does SIM fit in the larger framework of other missions and other techniques? ***YES***
   - SIM does unique planet science that no other planned mission can/will do
   - TPF needs SIM (technology, target identification, planet masses)
2. Is SIM feasible from an engineering and technology perspective? ***YES***
   - SIM new design is much less complex and risky than the Reference Design, and is now no more complex than missions that have successfully flown (per the SIMTAC)
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap? ***YES***
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets? ***NO***
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry? ***YES***
   - This capability allows SIM to detect long-period (>5 year) planets necessary for TPF
   - Global Astrometry is a key science capability endorsed by the Decadal Reports

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(Backkup) Science Comparison

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SIM Space Interferometry Mission

Current Alloc.	Shared BL	SONATA	PARASIM	
Deep Search	89	33	15	[redacted]
Broad Survey	890	330	150	
Young Stars	130	67	36	
other NA	221	114	61	

Time Allocated	
Deep Search	
Broad Survey	10.30%
Young Stars	3.70%
Narrow Ang Astro	6.00%
Wide Ang Astro	15.00%

CMG's have 400 times the torque of the reaction wheels used in yellow boxes.

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Space Interferometry Mission

SIM

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ERB SIM Cost Summary
Rev 2 for external release

Jim Marr

SIM Deputy Project Manager

Revised 3 April 2001

Cost Challenges

JPL

Space Interferometry Mission

SIM

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- Resolve differences between IPAO Independent Assessment (IA) Independent Cost Estimates (ICE's) and SIM's internal bottoms up estimate. **STATUS: Resolved**
  - Found SIM did not communicate its design, acquisition, and buildup process to the IA's cost estimators during the IA.
    - Fixed: spent the time to answer all of the cost estimator's questions (few 100 hours)
  - Reduced the differences on the SIM Reference Design to well within 20%
- Develop accurate cost estimates for each of the SIM mission design options under study. **STATUS: Complete**
  - Used Price H & S cost models to help estimate costs or cost deltas for each design. Worked closely with IPAO to ensure full design detail communicated.
  - Using the Price model results, verified:
    - costs for Phase B & C/D
    - predicted system mass
  - Cost estimates agree with IPAO ICE's to within 10%
  - Difference in cost between the most and least capable designs is $45M
- Cost estimates for all three designs to meet NASA $930M cost cap. **Status: Achieved**
  - Includes Phases B/C/D costs, launch vehicle, and Interferometry Science Center

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SIM Space Interferometry Mission

External Review Board
SIM Technology Development

Bob Laskin
SIM Project Technologist

22 & 23 March 2001

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Outline

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SIM Space Interferometry Mission

- The technology challenge
- Status of the technology
- Roadmap to completion
- Impact of the new design options

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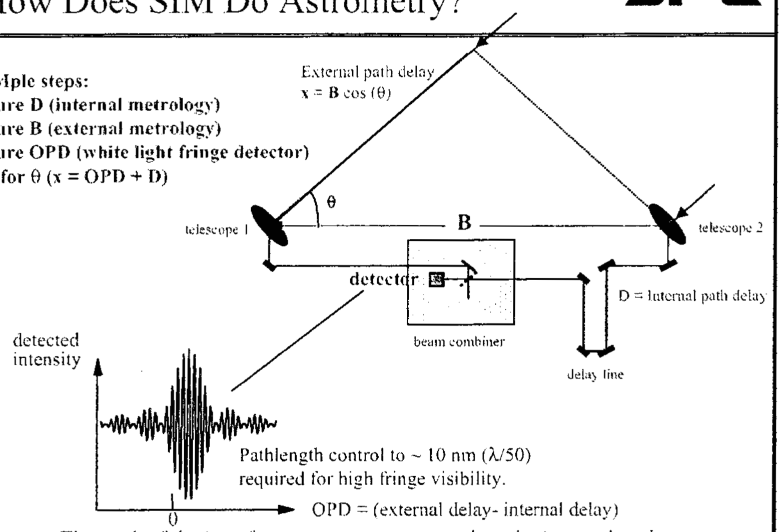
How Does SIM Do Astrometry?

Four SIMple steps:

1. **Measure D (internal metrology)**
2. **Measure B (external metrology)**
3. **Measure OPD (white light fringe detector)**
4. **Solve for θ (x = OPD + D)**



- *The peak of the interference pattern occurs when the internal path delay equals the external path delay*

SIM Space Interferometry Mission

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SIM Technology Challenges

- Picometer knowledge (100 pm = diameter of a hydrogen atom)
  - Picometer laser metrology
  - Picometer starlight fringe position measurement
  - Data post-processed on ground to achieve astrometry science
- Nanometer control (75,000 nm = thickness of a human hair)
  - Needed for high SNR fringe => picometer fringe measurement
- Millikelvin thermal stability of optics
- Overall instrument complexity
  - Autonomous operation
  - Instrument modeling, integration and test
- The technology challenges, and approach to addressing them, are fundamentally the same for Classic and for the three new design options

SIM Space Interferometry Mission

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Reference Design Astrometric Performance
-- based on "today's" component technology

SIM Space Interferometry Mission

	Parameters	Parameter Performance Today	Parameter Performance Needed by SIM	SIM Wide angle (WA) & Narrow Angle (NA) Performance
1	**Beam launcher thermal sensitivity (bulk, gradient)**	100 pm/mK, 2500 pm/mK	2 pm/mK, 50 pm/mK	28 μas/ 4.8 μas
2	**Cyclic averaging residual error per gauge**	50 pm	5 pm	4.3 μas/ 1.8 μas
3	**Pointing dither error per gauge**	750 mas	75 mas	5 μas/ 2.8μas
4	Corner cube surface quality	lamda/100	lamda/500	5 μas/ 1.2μas
5	Wide angle error due to beam diffraction	1000 pm	100 pm	8.5 μas (WA)
6	Narrow angle error due to beam diffraction	67 pm	2.7 pm	1.7 μas (NA)
7	Wide angle error due to polarization effects on corner cubes	375 pm	15 pm	10 μas (WA)
8	Narrow angle error due to polarization effects on corner cubes	25 pm	1 pm	2 μas (NA)
9	1-D absolute metrology accuracy	30 pm	3 pm	4 μas/1.2μas
10	Wide angle PSS end-to-end thermal deformation	100 pm	10 pm	4.4 μas (WA)
11	Narrow angle PSS end-to-end thermal deformation	10 pm	1 pm	0.9 μas (NA)
12	Systematic fringe measurement error	150 pm	30 pm	4.4 μas/ 1.9 μas
	Wide Angle Performance (General Astrophysics) 4 μas (goal); 30 μas (min)	**29 μas**	**3.9 μas**	
	Narrow Angle Performance (Planet Detection) 1 μas (goal); 3 μas (min)	**6 μ as**	**0.8 μas**	

High confidence via experiment in SIM-like configuration/environment or previous experience

Moderate confidence via analytical result or experiment in less SIM-like configuration/environment

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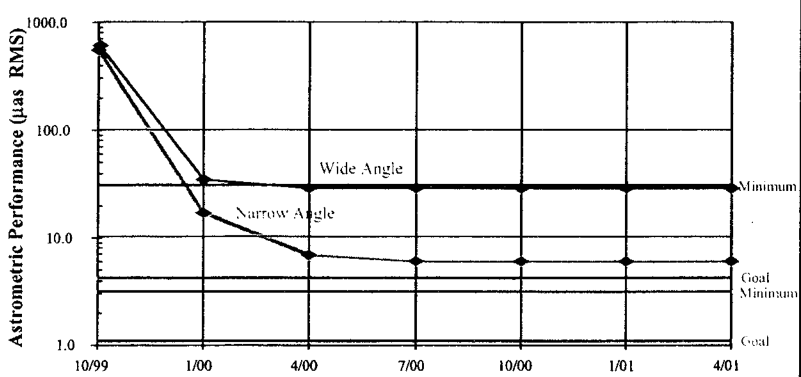
SIM Performance Metric -- Progress

SIM Space Interferometry Mission

- Calculated Wide Angle based on Component Performance
- Calculated Narrow Angle based on Component Performance



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Picometer Technology -- Approach

SIM Space Interferometry Mission

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- Develop and test the basic building blocks
  - Metrology Source -- laser, stabilizer, frequency shifter and modulator, fiber optic distribution system
  - Picometer Gauge -- beam launcher, corner cubes, detector, readout electronics
  - White light fringe detector / camera
- Test metrology gauges individually and in "optical trusses"
  - Test gauges "back-to-back" for consistency: 2-Gauge Experiment
  - Test multiple gauges in a truss geometry similar to SIM external metrology truss: 6-Gauge Experiment
- System test metrology gauges in combination with white light fringe measurements -- SIM's basic measurement technique
  - Microarcsecond Metrology (MAM-1) Testbed: single baseline interferometer demonstrates ability to measure differential positions of stars to microarcsecond level across field of regard
- Test deformation of "large" optics over milliKelvin thermal gradient changes -- Thermal Optomechanical (TOM) Testbed

Picometer Experiment Flow

SIM Space Interferometry Mission

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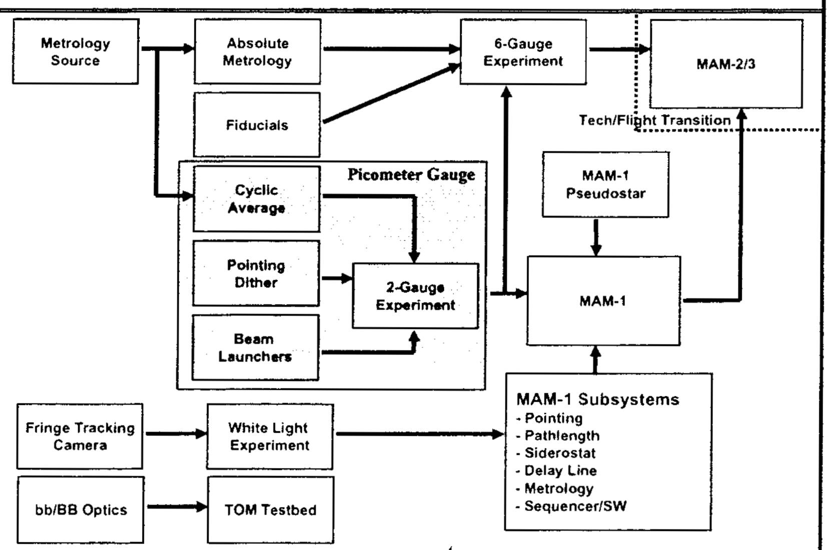

Picometer Metrology Gauge
-- using polarization to launch the beam

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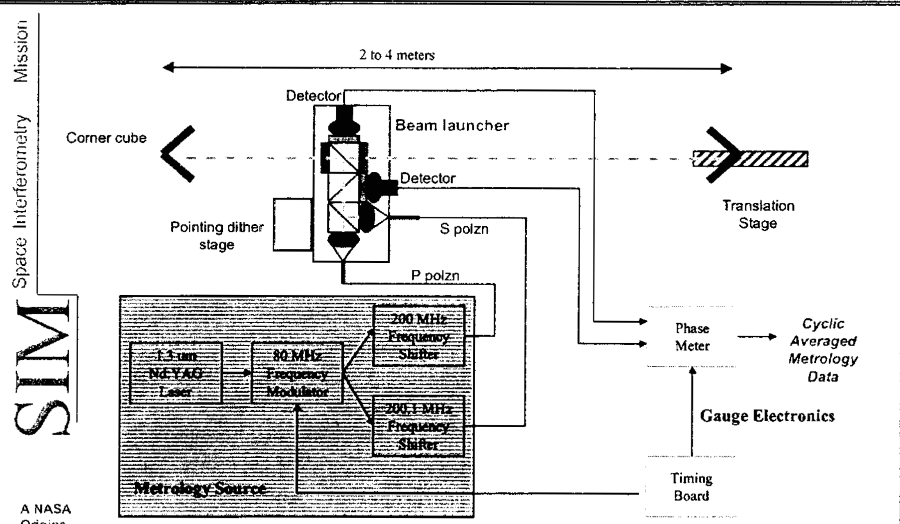
SIM Space Interferometry Mission



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Picometer Metrology Gauge
-- compensating for polarization leakage

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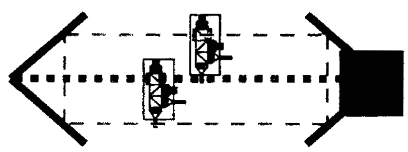
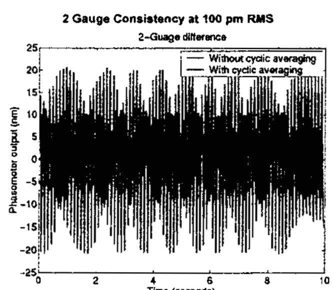
SIM Space Interferometry Mission



"2-Gauge" Experiment

Heterodyne Metrology Gauge

- SIM will use these gauges to monitor relative motion of optics
- Gauge precision maps directly to science precision: 30 pm <=> 1 uas
- Recently demonstrated 50 pm gauge consistency in the "2-Gauge" experiment -- targeting another order of magnitude



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Beam Launcher Thermal Sensitivity
-- Measured in 2-Gauge Experiment

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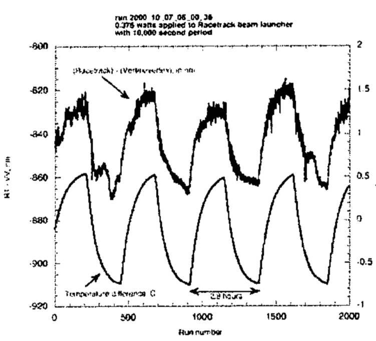
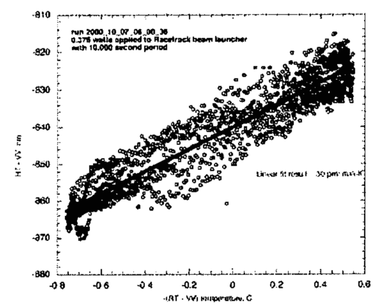
SIM Space Interferometry Mission





-- Measurement of 'interim' Race-track beam launchers by Peter Halverson.
-- Two gauges measure distance between two corner cubes, one gauge is heated while the other is held at constant temperature (dT << 1 deg).
-- These launchers exhibited 30 pm/mk thermal sensitivity.
-- Requirement is < 3 pm/mK

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Picometer Metrology Gauge
-- non-polarizing concept (aka NextGen launcher)

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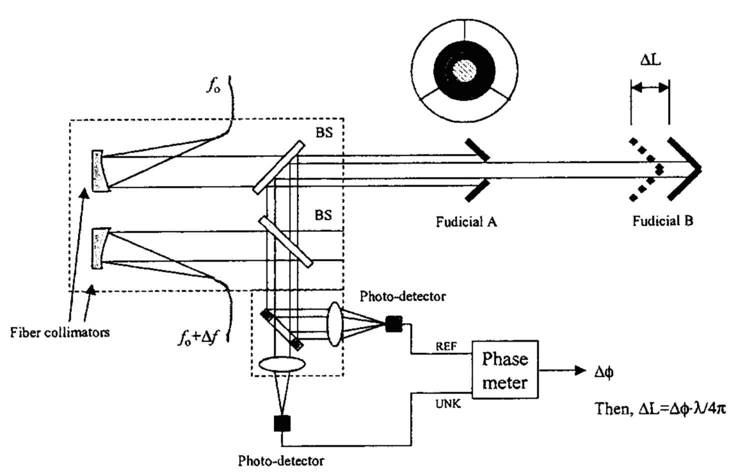
SIM Space Interferometry Mission



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Proof-of-Concept Experiment

SIM Space Interferometry Mission

- Lab demonstration was done with CoPHI (Common Path Heterodyne Interferometer)
- 532nm laser
- 50mm beam size
- Fiducial A is a flat mirror with a central hole (0.25" dia)
- Fiducial B is a flat mirror mounted on a PZT
- Setup in still air

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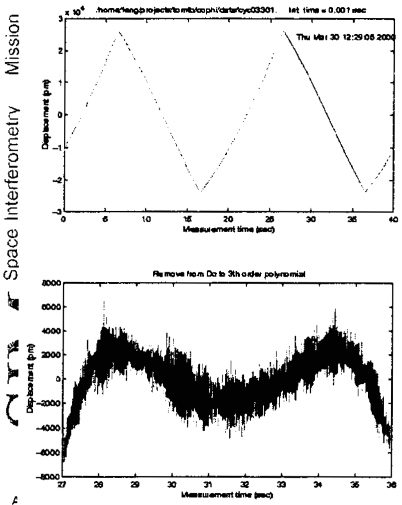
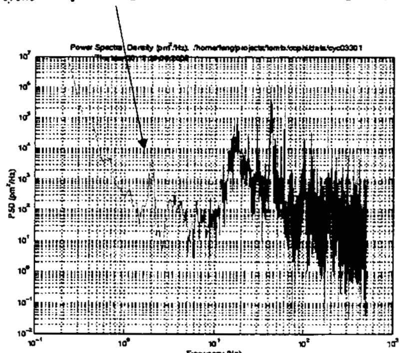
Small Cyclic Error

SIM Space Interferometry Mission



- Measured cyclic error to be ~20pm RMS

$$\varepsilon_{cyclic} \approx \sqrt{4000\,pm^2 / Hz * 0.1Hz} = 20\,pm(RMS)$$



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Excellent Thermal Stability

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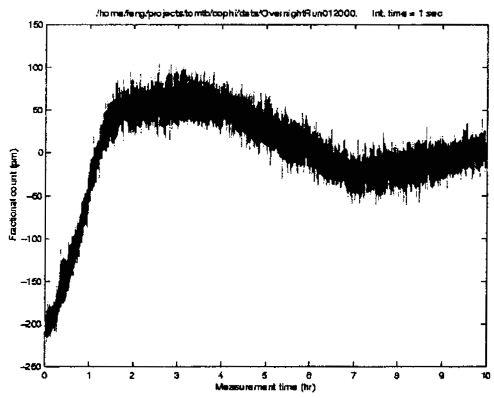
SIM Space Interferometry Mission

- Data indicate that the instrument is stable to better than 100pm over 1 hr (temperature stability estimated ~100mK)



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SIM Performance Metric

-- with proof-of-concept NextGen beam launcher

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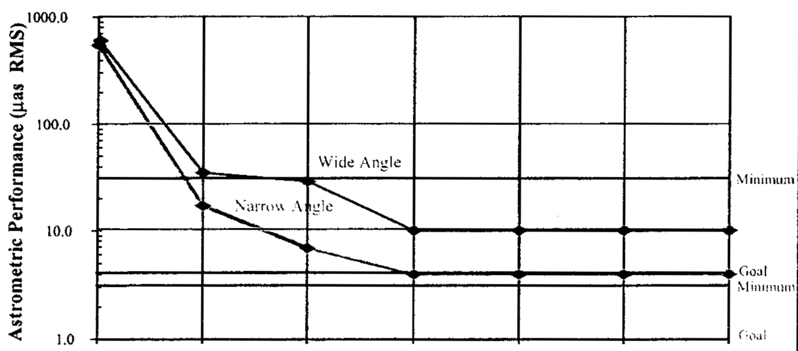
SIM Space Interferometry Mission

- Calculated Wide Angle based on Component Performance
- Calculated Narrow Angle based on Component Performance



A NASA Origins Mission

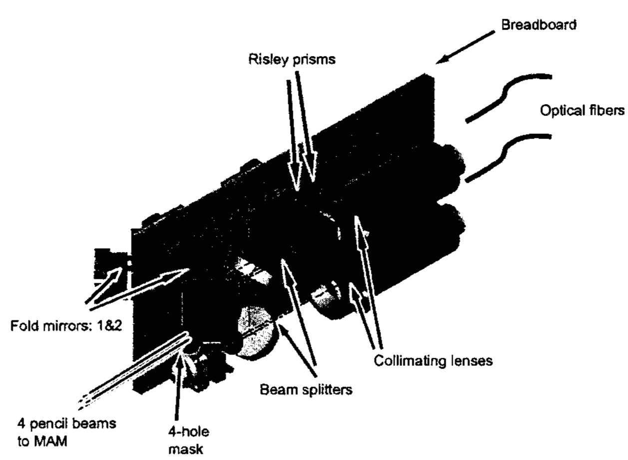
Beam Launcher Status

SIM Space Interferometry Mission

- New (NextGen) Beam Launchers
  - Breadboards of the leading internal and external launcher designs are in process
    - Proceeding with SAVV (sub-aperture vertex-vertex) version of internal launcher
      - Should be complete with initial test data by May
      - Will be incorporated into the MAM-1 Testbed by June
    - Quick prototype (QP) of external launcher also underway
      - Possible schedule slip due to vendor time for precision optics
      - Should be complete with initial test data in June timeframe
- Old Beam Launchers
  - Decided to complete build of three launchers to the old "athermalized beam launcher" design
  - Gives LM team first experience with beam launcher assembly
  - Will help wring out 2-Gauge thermal testing apparatus

CAD Layout of "Interim" SAVV

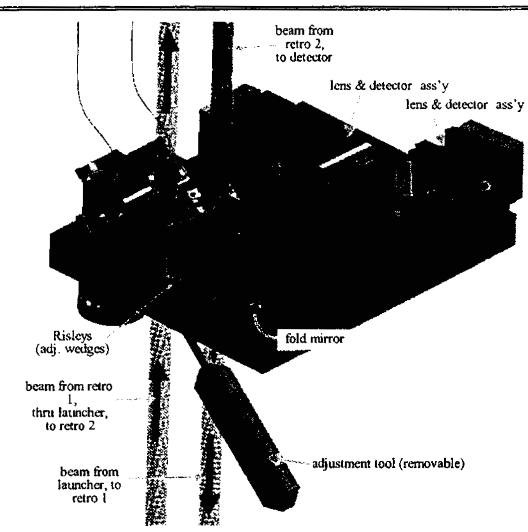
SIM Space Interferometry Mission



CAD Layout of QP

JPL

SIM Space Interferometry Mission

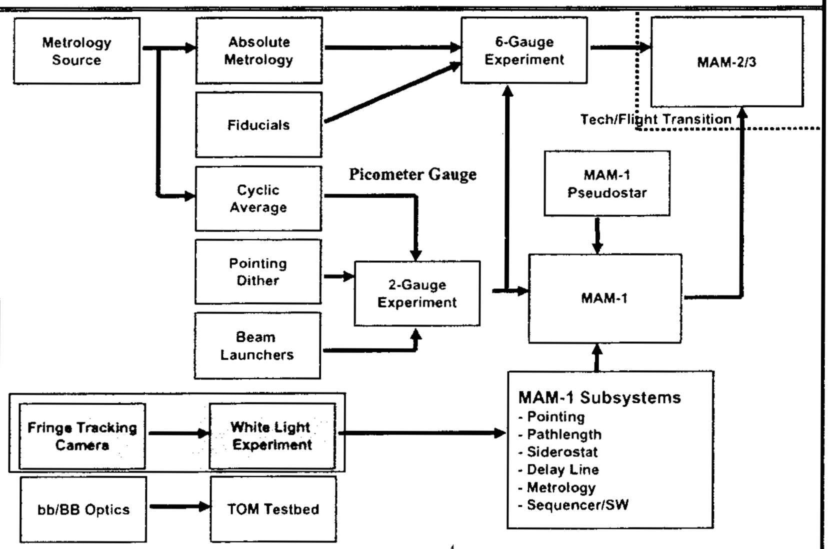


A NASA Origins Mission

Picometer Experiment Flow

JPL

SIM Space Interferometry Mission



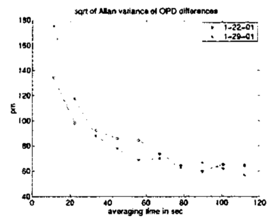
A NASA Origins Mission

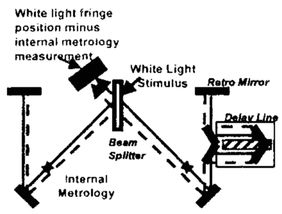
White Light Experiment -- Status

JPL

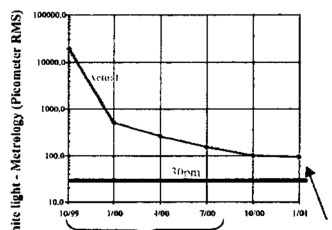
SIM Space Interferometry Mission

- Objective: Demonstrate white light fringe position measurement at the picometer level
- Performance goal: 10 - 30 pm
- Current performance: 90 pm





Simplified representation

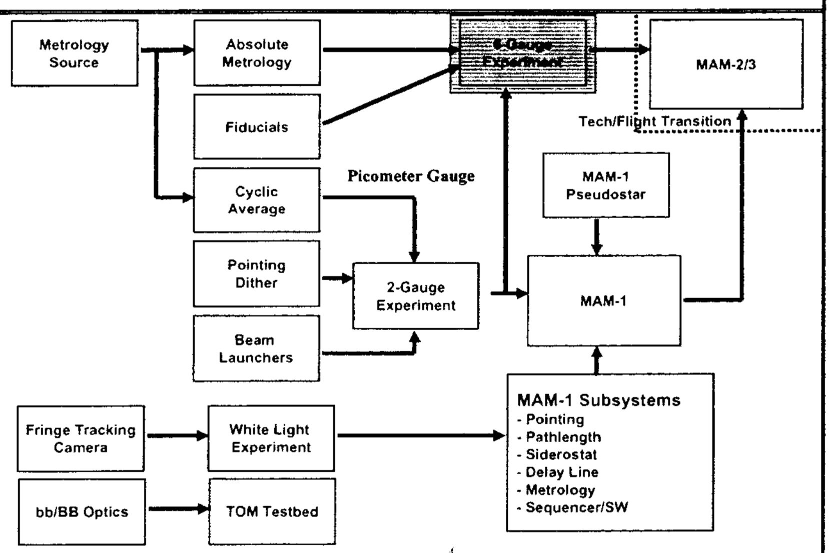


A NASA Origins Mission

Picometer Experiment Flow

JPL

SIM Space Interferometry Mission



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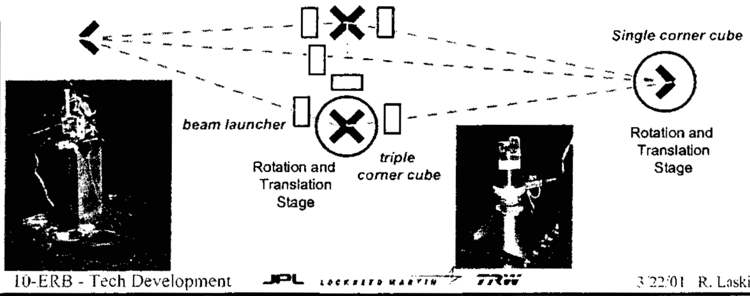
6-Gauge Experiment

-- building laser gauges into metrology trusses

JPL

SIM Space Interferometry Mission

- SIM external metrology system is a large scale metrology "truss"
- 6-Gauge demonstrates a picometer metrology truss in two dimensions
  - Use redundant metrology truss to measure the errors due to corner cube motions (rotations and translations)
    - corner cube surface imperfections
    - polarization effects
- Status: experiment under construction with initial data expected later this year

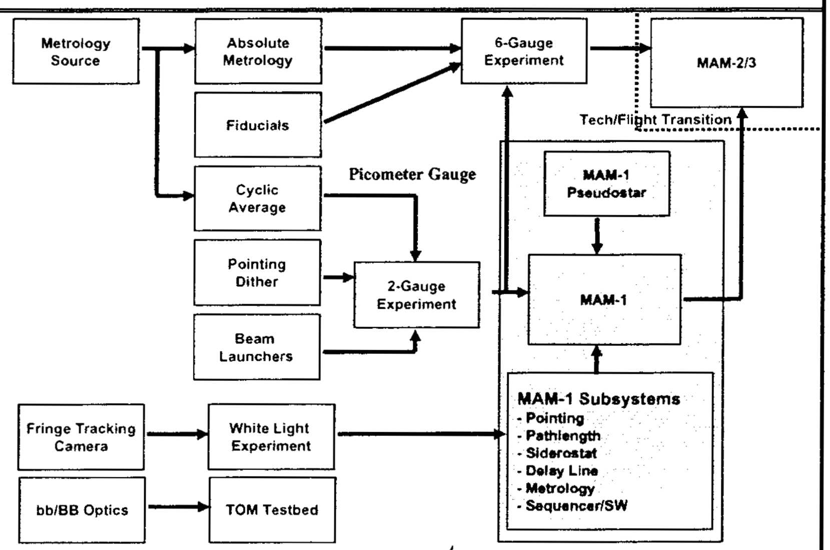


A NASA Origins Mission

Picometer Experiment Flow

JPL

SIM Space Interferometry Mission



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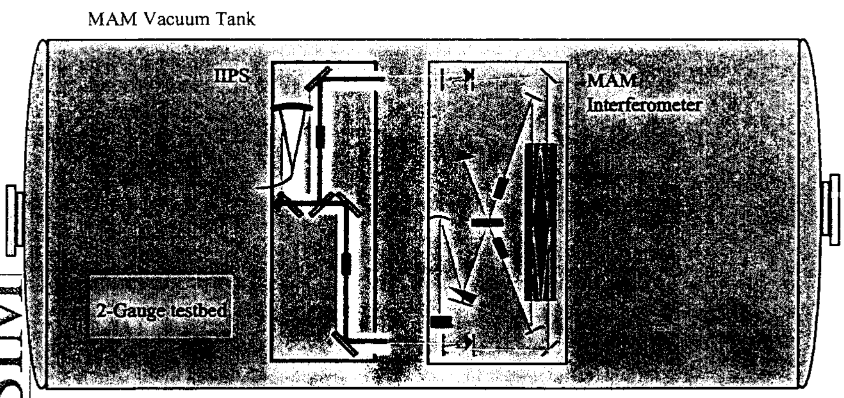
Microarcsecond Metrology (MAM-1) Testbed

JPL

SIM Space Interferometry Mission



- Testbed Objectives
  - Demonstrate ability to measure differential positions of stars to microarcsecond level across field of regard
  - Validate models used for instrument calibratation

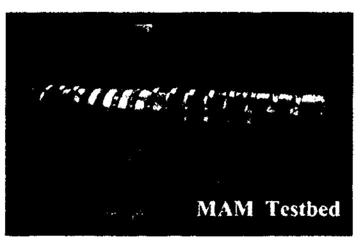
A NASA Origins Mission

MAM-1 -- Status

JPL

SIM Space Interferometry Mission

- Back end of testbed interferometer operational in MAM-1 vacuum tank
  - White light experiment
- Inverse interferometer pseudostar (IIPS) in assembly at LM
- Integration of IIPS to MAM-1 test article to begin this spring
- Interim SAVV will be ready by June (May is target)
- Expect "first fringes" this summer



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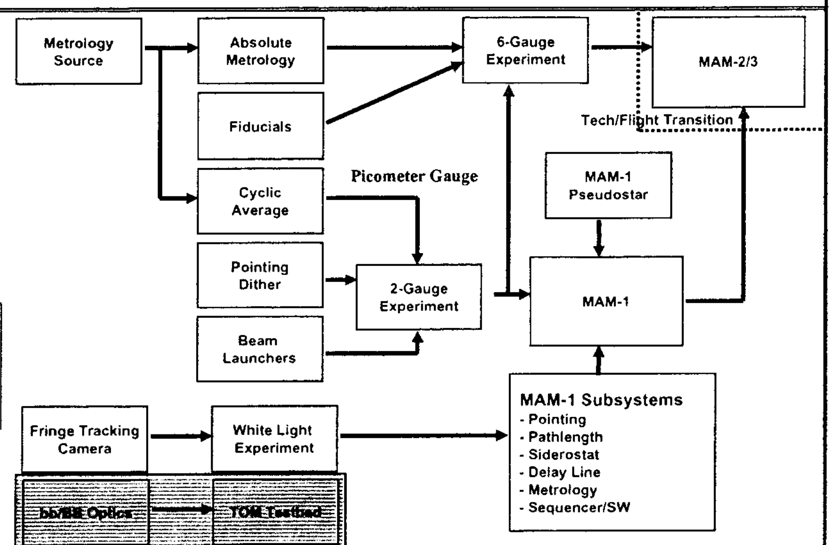
Picometer Experiment Flow

SIM Space Interferometry Mission



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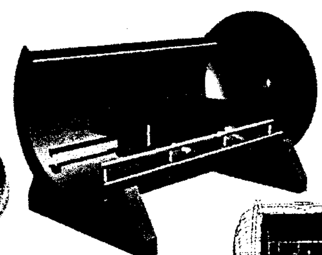
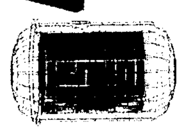
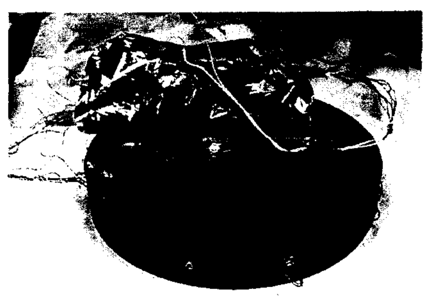
Thermal Optomechanical (TOM) Testbed

-- mK thermal control means pm deformations

SIM Space Interferometry Mission

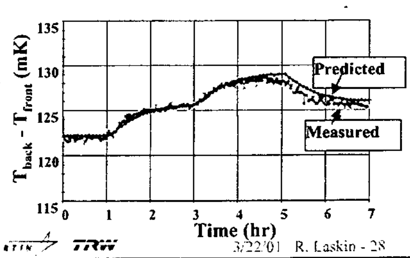






TOM Testbed Progress & Plan

- Demonstrated ability to accurately model temperature gradient changes on SIM-scale optics (33 cm) -- predictions good to about 20% in the mK regime
- Next step -- correlate mK temperature changes with pm mirror figure changes

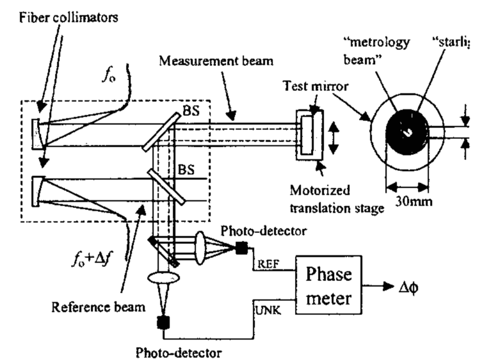


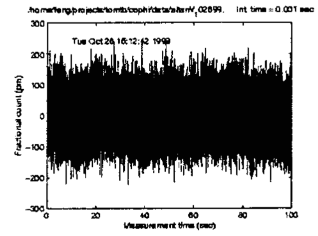
A NASA Origins Mission

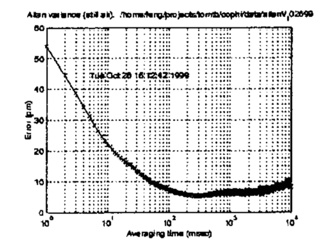
COPHI

-- a "super-zygo" to measure pm optics deformations

SIM Space Interferometry Mission







A NASA Origins Mission

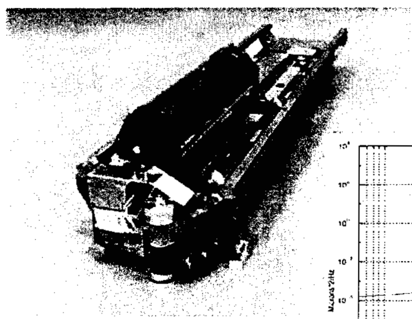
Nanometer Technology -- Approach

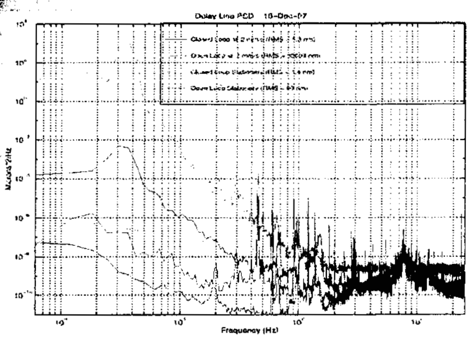
SIM Space Interferometry Mission

- Develop and test the basic building blocks
  - Optical delay line
  - Vibration isolation
  - Precision structures and mechanisms
  - Realtime control software
- Test stability of precision structure under anticipated thermal environment
  - Sub-structure Test Article (SSTA)
- System test that components work together to provide nanometer stability of starlight fringes in response to expected on-orbit disturbances
  - STB-1: single baseline interferometer demonstrates: (1) ability of guide interferometer to track stellar fringes and spots; (2) ability to accurately model end-to-end performance of dynamics & control systems
  - STB-3: three baseline interferometer with full metrology truss demonstrates: (1) ability to stabilize dim star science fringes using pathlength feedforward; (2) ability to stabilize dim star science spots using angle feedforward; (3) ability to integrate a multi-loop realtime control system of similar complexity to SIM's
    - **STB-3 transfers to RTC subsystem as flight system development testbed**

A NASA Origins Mission

Brassboard Optical Delay Line



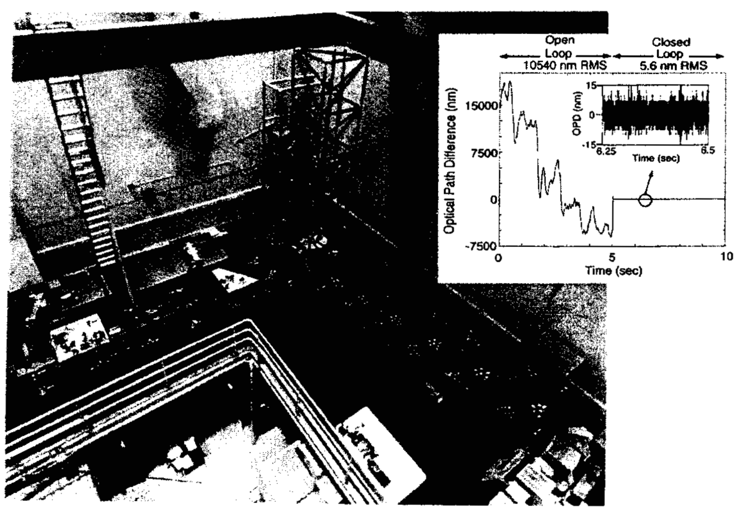


- *Performance tested*
  - *1.4 nm RMS stationary*
  - *3.3 nm RMS at 2 mm/s*
- *Environmentally tested*
  - *vibration, shock, thermal*

SIM Space Interferometry Mission

A NASA Origins Mission

Micro-Precision Interferometer Testbed
-- aka STB-1



SIM Space Interferometry Mission

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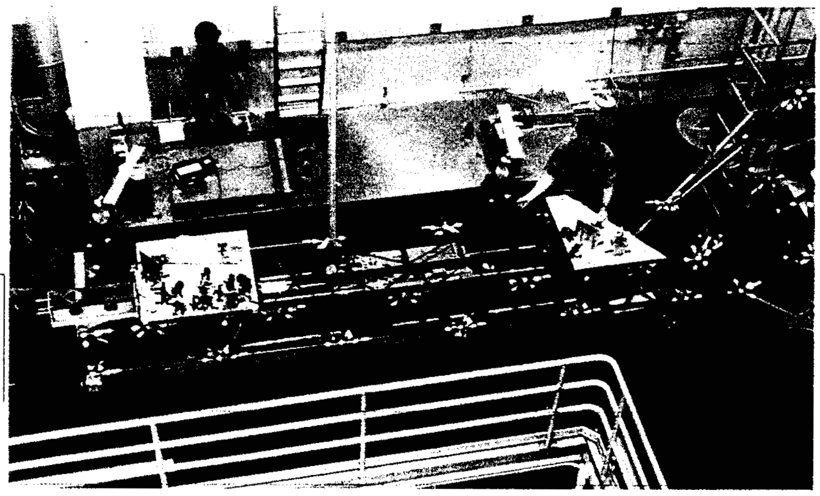
MPI Optics Boom

JPL

SIM Space Interferometry Mission



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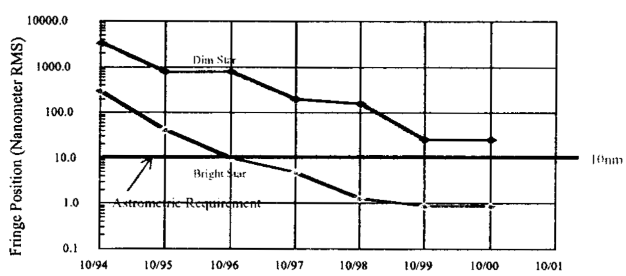
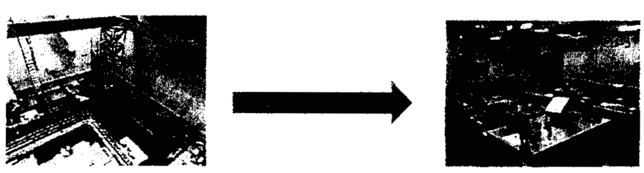
Progress in Nanometer Stabilization

JPL

SIM Space Interferometry Mission





MPI Testbed

SIM System Testbed

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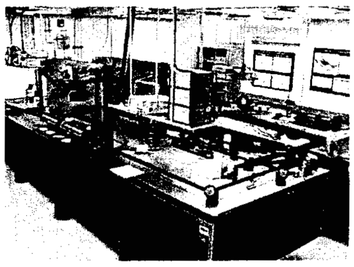
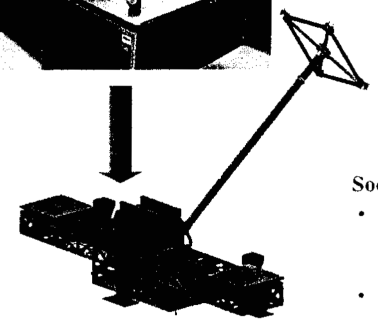
SIM System Testbed (STB-3)
-- nanometer control at full scale, full complexity

JPL

SIM Space Interferometry Mission



Now: 3 baselines on optical tables
- Initial 3 baseline functionality and performance against ACS disturbance
- Completed fabrication of 9-meter flexible structure



Soon: 3 baselines on structure
- Begin nanometer active control experiments on flexible structure
- Three baselines, full scale

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SIM System Testbed (STB-3)
-- initial results on optical tables

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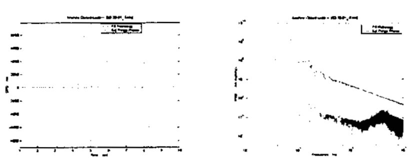
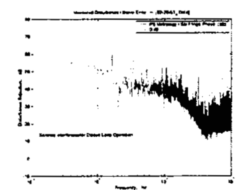
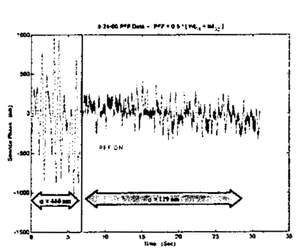
SIM Space Interferometry Mission

Closed Loop Performance Guide Stars





Closed Loop Performance Science Star



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Pico Technology Impacts

JPL

SIM Space Interferometry Mission

- Many things are common to all options
  - Metrology performance requirements ~ same in all designs
  - White-light performance requirements ~ same in all designs
  - MAM-1 remains critical
  - TOM continues -- incorporates appropriate compressor brassboard
  - *New challenge -- demo double corner cube mounted to sid with cutouts*
- There are some discriminators
  - SONATA does not need absolute gauge development
  - *SONATA needs demonstration of chopping FAM in MAM-1*
    - Considered significant threat to formulation phase schedule & budget

A NASA Origins Mission

Nano Technology Impacts

JPL

SIM Space Interferometry Mission

- Many things are common to all options
  - Optical stabilization requirements same in all designs
  - PSS size and configuration very similar in all designs
    - STB-3 easily modified to emulate Shared Baseline or ParaSIM
  - Designs require similar RTC functionality (multi-baseline operation, siderostats for acquistion and line-of-sight pointing)
- There are some discriminators
  - ParaSIM may need a more agile ACS => larger RWA's or CMG's
    - CMG's would require a different approach to vibration attenuation
    - STB-3 modifications would result
  - Baseline attitude placement accuracy requirement tighter for ParaSIM
    - May drive PSS thermal deformation requirements
    - SSTA requirements would be tightened

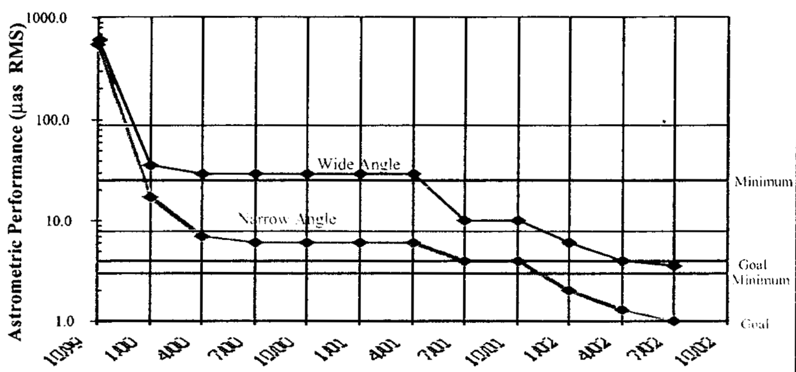
A NASA Origins Mission

Overall Technology Impacts

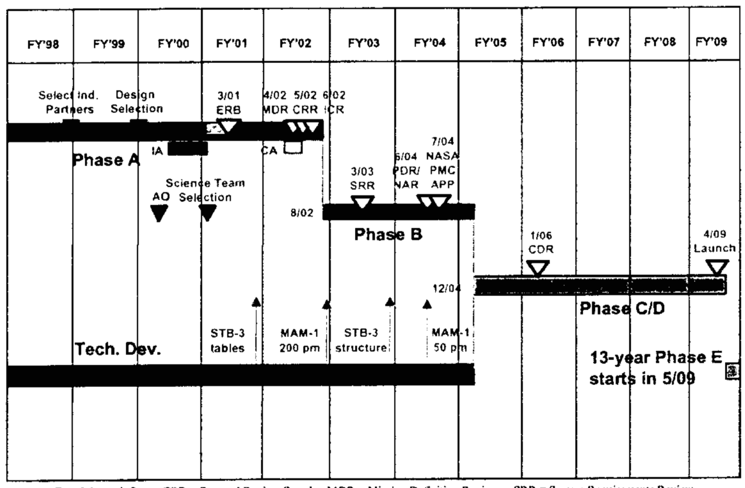
- The design options lead to essentially the same technology development effort as is currently planned for the reference design
  - None of the options results in the complete elimination of a testbed or the addition of a new one
- Comparing the options
  - Validation of the chopping FAM for SONATA is a significant cost and schedule threat
  - ParaSIM may push the nanometer technology a little harder
  - Shared Baseline is the closest to the reference design

SIM Performance Metric -- Future Progress

- Calculated Wide Angle based on Component Performance
- Calculated Narrow Angle based on Component Performance



SIM Project Schedule



ATLO = Assy, Test & Launch Ops
CA = Confirmation Assessment
CDR = Critical Design Review
CR = Confirmation Review (NASA PMC)
ERB = External Review Board
IA = Independent Assessment
I&T = Integration & Test
MDR = Mission Definition Review
NAR = Non Advocate Review
PDR = Preliminary Design Review
NASA PMC = Programmatic Management Council (APP = Approved)
SRR = System Requirements Review
CRR = Confirmation Readiness Review (JPL PMC)
ICR = Initial Confirmation Review (Code S)

Technology Assessment

SIM Space Interferometry Mission

- We have come a long way
  - Nanometer technologies are nearly in hand
  - Significant progress has been made in picometer technology, and considerable momentum has been built
    - Closing in on the elusive beam launcher for the picometer metrology gauge -- our last major component hurdle
- We still have a ways to go
  - New beam launchers must be proven to work at SIM form factors
  - Picometer system testbeds are very challenging

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Five Key Questions

JPL

SIM Space Interferometry Mission

1. Does SIM fit in the larger framework of other missions and other techniques?
   - SIM does unique science that no other planned mission can will do
   - TPF needs SIM (technology, target identification, planet masses)
2. Is SIM feasible from an engineering and technology perspective?
   - SIM new design is much less complex and risky than the Reference Design, and is now no more complex than missions that have successfully flown (per the SIMTAC)
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap?
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets?
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry?
   - This capability allows SIM to detect long-period (>5 year) planets necessary for TPF
   - Global Astrometry is a key science capability endorsed by the Decadel Reports

A NASA Origins Mission

SIM-Shared Baseline Design

Space Interferometry Mission
SIM

The SIM Team
(presented by Alan L. Duncan)
22- March-2001

A NASA Origins Mission

Outline

Space Interferometry Mission
SIM

- **Introduction**
- **Design Description**
  - **What does it look like…how does it work**
  - **Technology drivers**
  - **Performance drivers**
  - **Redundancy approach**
- **Test approach**
  - **flight system**
  - **system testbeds (STB3, MAM2/3)**
- **Calibration approach**
- **Summary**

A NASA Origins Mission

Why "Shared Baseline"?

- Substantially reduce external metrology parts count
- Simpler external metrology boom
- Reduce number of siderostat/gimbal assemblies (big cost driver for starlight subsystem)
- Eliminate starlight subsystem switchyard (cost and risk driver)
- Eliminate nuller

SIM Space Interferometry Mission

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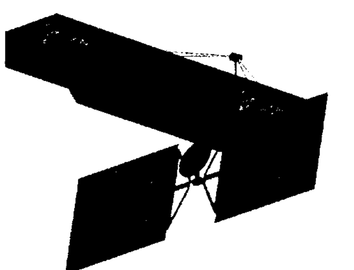
Shared Baseline SIM



- Engineering Delta
  - Greatly reduces external metrology boom complexity, and reduces number of beams from 36 to 18
  - Two Baselines, one shared by two Guide Interferometers and one shared by two Science Interferometers
  - Two interferometers on a single baseline share siderostat mirrors and use wide field-of-view of TMA (Three-Mirror Anastigmat) telescopes
- Description
  - Combines the best of SIM-Classic and SIM-SOS into a lower cost design
  - Most similar to SIM-Classic design
    - Best understood of the options
    - Best performance of the options
  - Best redundancy capability
  - Provides descope options
- Science Capability
  - Retains Level 1 planet finding req'ts
  - Retains capability to do the GRID
  - Retains Level 1 global astrometry capability requirements
  - Imaging Demonstration capability
    - Limited U,V point ring
  - No nulling capability

SIM Space Interferometry Mission

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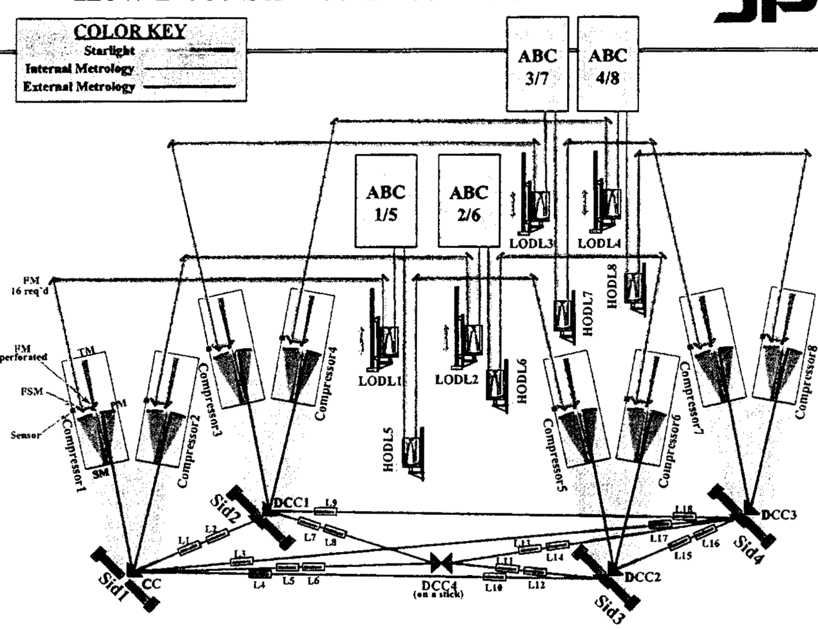
How Does Shared Baseline SIM Work?

JPL

SIM Space Interferometry Mission



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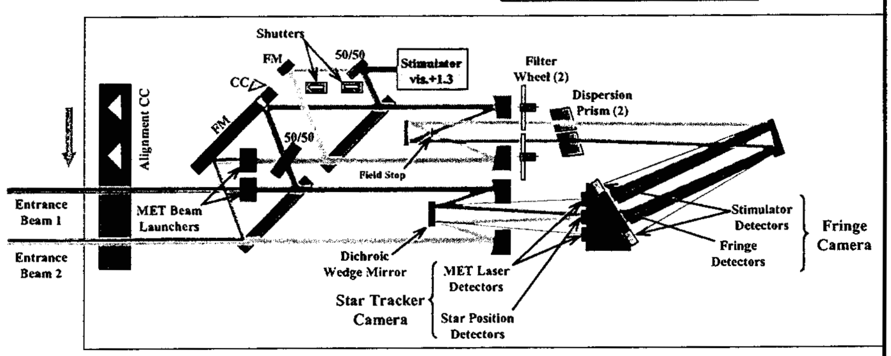
How Does Shared Baseline SIM Work?

JPL

SIM Space Interferometry Mission

ACRONYM KEY
- ABC - Astrometric Beam Combiner
- CC - Corner Cube
- DCC - Double Corner Cube
- FM - Fold Mirror
- FSM - Fast Steering Mirror
- L - Metrology Beam Launcher
- PM - Primary Mirror
- Sid - Siderostat Mirror
- SM - Secondary Mirror
- TM - Tertiary Mirror
- HODL - High Bandwidth Optical Delay Line
- LODL - Low Bandwidth Optical Delay Line

Astrometric Beam Combiner Schematic



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Shared Baseline Design Detail
(page 1 of 6)

JPL

SIM Space Interferometry Mission

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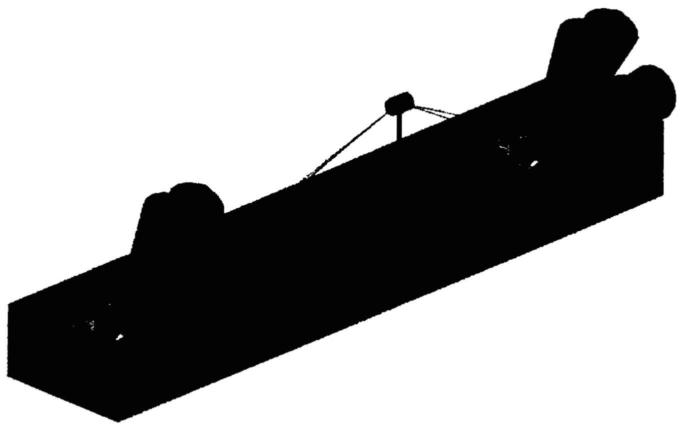

Shared Baseline Design Detail
(page 2 of 6)

JPL

SIM Space Interferometry Mission

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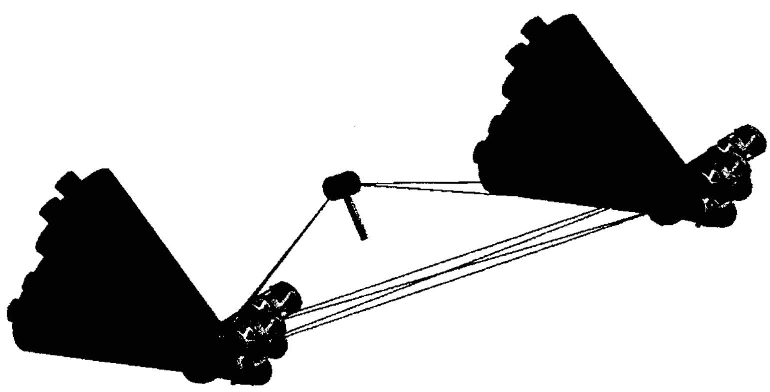

Shared Baseline Design Detail (page 3 of 6)

SIM Space Interferometry Mission

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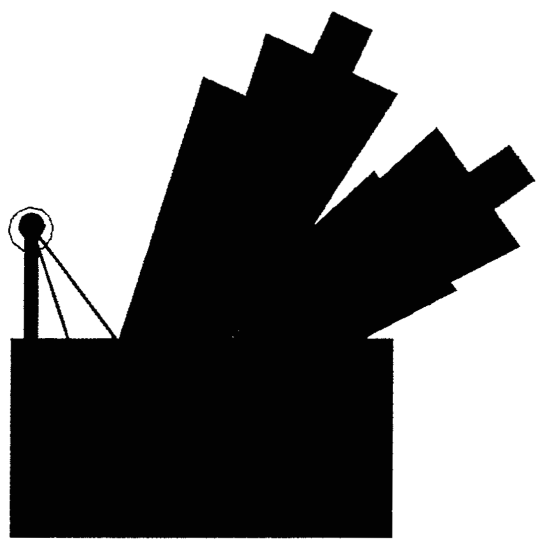
Shared Baseline Design Detail (page 4 of 6)

SIM Space Interferometry Mission

A NASA Origins Mission



Shared Baseline Design Detail
(page 5 of 6)

JPL

SIM Space Interferometry Mission

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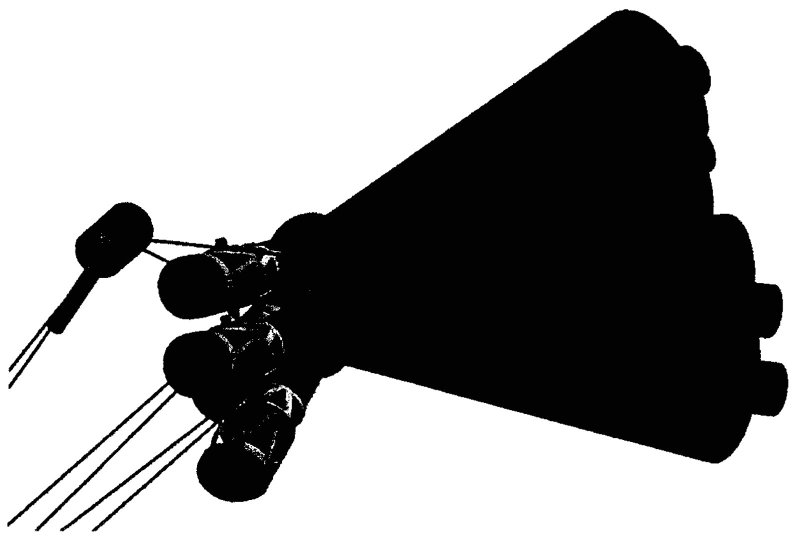

Shared Baseline Design Detail
(page 6 of 6)

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SIM Space Interferometry Mission

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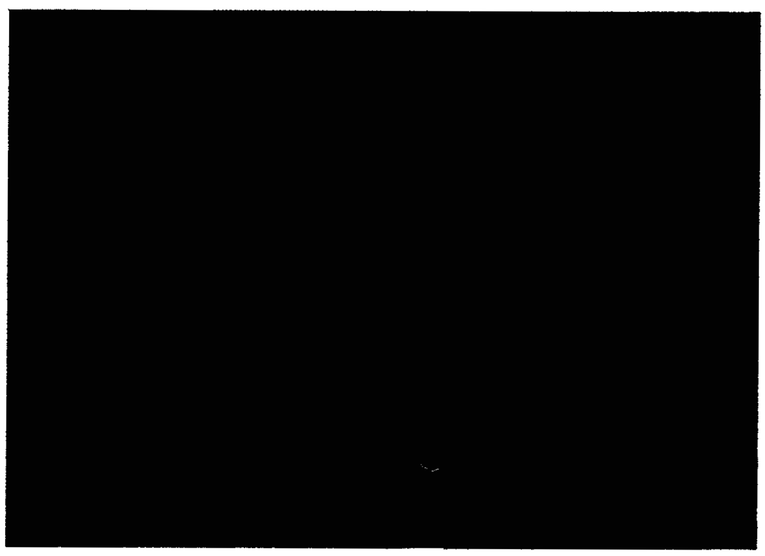


Potential Technology Drivers

JPL

- "Fixed", Wide Field of View Compressors
  - field of view steering / beamwalk
  - centered, internal racetrack metrology gauges
- Back to Back Double Corner Cubes
  - CC fabrication (probably no)
  - CC mounting on siderostat (probably yes)
  - other alternatives

Shared Baseline Requires Minimal New Technology Compared to the Reference Design

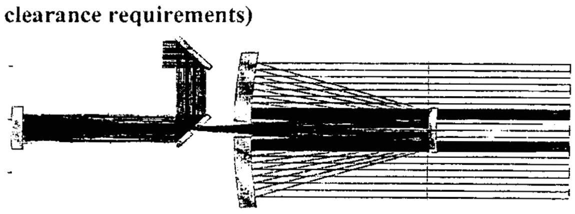
SIM Space Interferometry Mission

A NASA Origins Mission

"Fixed" Guide Star Compressors (with optically steered line of sight)

JPL

- Approach
  - common siderostat allows steering of both guide stars line of sight (not independently) to acquire one guide star; the second guide star is acquired by optically steering through the compressor FOV and rotation of the spacecraft
  - common siderostat for science interferometers is used to slew line of sight for collection of science targets in tile (only one science interferometer can be used; the other is for redundancy only)
- Design Description
  - three mirror anastigmat compressor design (TMA)
  - 0.2 degree by 1.5 degree field of view (constrained by metrology beam clearance requirements)



SIM Space Interferometry Mission

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Potential Performance Drivers

- External Metrology Truss "Multipliers" For the More Compressed Geometry (evaluate error budget impacts)
- Centered TMA Obscurations / Diffraction / compatibility with metrology beam launcher design (design trades / analysis underway)
- Guide Star FOV Limitations (probably no - maybe some small throughput impact)
- Fixed Guide Star Beamwalk Due to Residual Spacecraft Motion (no - first order correction with common siderostat, if necessary - evaluate error budget impacts)
- Thermal (observations vs sun angles; more benign than SIM-Classic due to the substantial reduction in "exposed" external metrology)

Shared Baseline Performance Comparable to Reference Design With Reduced Risk

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Shared Baseline Performance Summary

Astrometric Accuracy	*Wide-Angle* (end of mission) (uas)	*Narrow-Angle* (single look)
Reference Design	3.87	0.82
Shared Baseline	4.77	1.00

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Effect of Shared Baseline Design Changes on Performance

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Design Change	Example of Impacted Physical Effect	Size of Effect (1-σ)	
		Reference Design	Shared Baseline
External Metrology Geometry	Single-measurement accuracy	81.5 pm	96.1 pm (due to this effect alone)
Switch to SAVV metrology	Metrology Beam Walk factor on Corner Cube	5.0 pm/beam	10.1 pm/beam
Greater angle between siderostat and compressor	Metrology Beam Walk on Corner Cube due to articulation	15.3 pm/beam	40.5 pm/beam
	Alignment of Corner Cube on Siderostat mirror	45.1 pm/beam	87.2 pm/beam
	Starlight Footprint change on Siderostat Mirror	15.1 pm / sid	52.3 pm / sid
	Effect of Mirror Coating Uniformity	5.8 pm / sid	15.8 pm /sid
Larger Central Obscuration	Brightness-dependent fringe measurement error	387 pm	466 pm

Thermal Issues Summary

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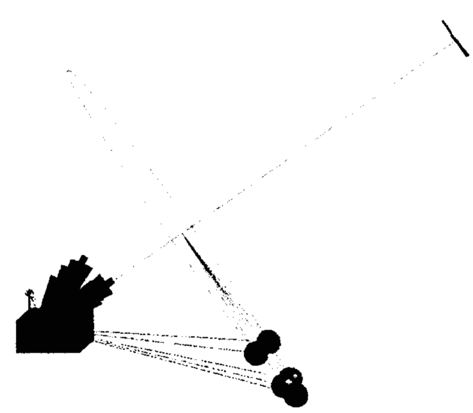
- Thermal environment expected to be more benign than SIM-Classic
  - no long external metrology boom with metrology launchers, associated mechanisms & electronics
- Sun exclusion angle study
  - analysis underway
  - first iteration of configuration optimization complete
  - will provide inputs to thermal model analysis



Shared Baseline Redundancy Approach

- Science Interferometer 1 or 2 Fails
  - use other science interferometer
- Guide Interferometer 1 or 2 Fails
  - science interferometers become the guide interferometers (science interferometer cannot share a common siderostat with a guide interferometer)
  - remaining guide interferometer becomes the science interferometer
- Common Siderostat Fails
  - "fixed" siderostat must be associated with the guide star pair (reduced science throughput due to additional spacecraft maneuvers to find guide stars)
- Shared Baseline can operate in a "ParaSIM" mode (constrained to a plane) with multiple failures

Shared Baseline Concept Provides Full Redundancy

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Flight System Test Objectives

- Functional Tests
- Environmental Tests
- Dynamics & Control (D&C) Tests (nanometer-level tests)
  - real time control loops (pathlength and angle stabilization and feed forward)
- Astrometric Tests (picometer-level tests)
  - white light fringe position
  - internal path length difference
  - science interferometer baseline rotations (pathlength information feed forward from guide star interferometers to the science interferometer)
  - repeatability and calibration validation

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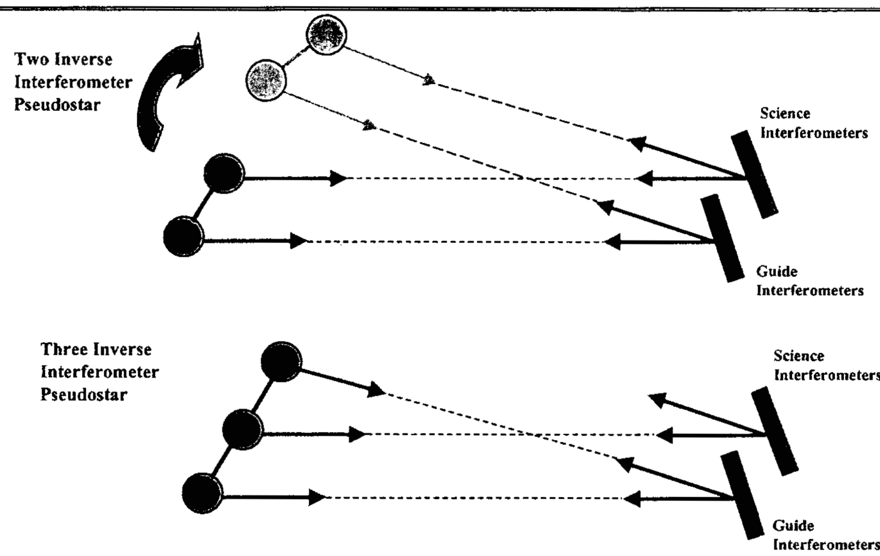
Pseudostar Approaches



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Trade Space Options

options	nanometer I&T approach	picometer I&T approach	nanometer system testbed	picometer system testbed
1	2 inverse interferometer pseudostar	2 inverse interferometer pseudostar	STB3	MAM2
2	3 inverse interferometer pseudostar (nanometer only)	2 inverse interferometer pseudostar	STB3	MAM2
3	3 inverse interferometer pseudostar (nanometer only)	2 inverse interferometer pseudostar	STB3	non-planar MAM3
4	3 inverse interferometer pseudostar	3 inverse interferometer pseudostar	STB3	non-planar MAM3

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Trade Space Options

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- Option 1: (two interferometer astrometric and D&C test, MAM2, STB3)
  - simplest flight system test option with a common 2 interferometer pseudostar for D&C and picometer testing
- Option 2: (two interferometer astrometric test, full three interferometer D&C test, MAM2, STB3)
  - requires additional interferometer (nanometer level requriements only) for D&C
- Option 3: (two interferometer astrometric test, full three interferometer D&C test, non-planar MAM3, STB3)
  - full three interferometer flight system testbed, but still only two interferometer astrometric test
  - ability to validate two interferometer astrometric test with a three interferometer system testbed
- Option 4: (three interferometer astrometric and D&C test, non-planar MAM3, STB3)
  - full three interferometer system testbed and flight system tests

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Options Ranking

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options	nanometer I&T approach	picometer I&T approach	picometer system testbed	Cost	Implementation Risk	Performance Risk
1	2 inverse interferometer pseudostar	2 inverse interferometer pseudostar	MAM2	low	low	medium +
2	3 inverse interferometer pseudostar (nanometer only)	2 inverse interferometer pseudostar	MAM2	medium	medium	medium
3	3 inverse interferometer pseudostar (nanometer only)	2 inverse interferometer pseudostar	non-planar MAM3	high	medium +	low +
4	3 inverse interferometer pseudostar	3 inverse interferometer pseudostar	non-planar MAM3	very high	high	low

- **blue shading: preferred options based on ranking**
- **implementation risk: risk that test program will not be successful**
- **performance risk: risk that flight system will not meet performance requirements on orbit**

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Risk Assessment

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options	Implementation Risk	Risk Assessment	Performance Risk	Risk Assessment
1	low	*Same as option 2 but using a* common pseudostar design for D&C and picometer testing, thus reducing implementation risk	medium +	*Same as option 2 but includes* additional risk of not performing D&C testing simultaneously for all controlled degrees of freedom
2	**medium**	**All flight system testing verified on system testbeds STB3 and MAM2; additional risk associated with scaling system testbed pseudostars**	**medium**	**Does not test the out of plane rotations of the 3rd baseline relative to the two that are tested by the pseudostar, risk mitigated by ability to perform complete test of shared baseline operation in a ParaSIM mode**
3	**medium +**	**Same as option 3 but with additional risk associated with more complex system testbed**	**low +**	**Risk of not doing a full three interferometer pseudostar test on the flight system mitigated by ability to validate two interferometer pseudostar test on the system testbed**
4	high	Complexity of *full 3 interferometer* out of plane testing on the flight system adds significant risk due to potential schedule impacts and increased difficulty in correctly interpreting data and properly controlling & measuring pseudostar degrees of freedom	low	Complete end to end ground test of the flight system

Flight System Test Summary

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- Combined flight system test approach / system testbed approach trade performed
- Trade options evaluated vs cost, implementation risk, and performance risk
- Two preferred options selected for further study
  - MAM 2 (picometer testbed), STB 3 (nanometer testbed), two inverse interferometer astrometric flight system test, & three inverse interferometer dynamics and control flight system test
  - MAM 3 (picometer testbed), STB 3 (nanometer testbed), two inverse interferometer astrometric flight system test, & three inverse interferometer dynamics and control flight system test
- For both options the performance risk (on orbit) due to the lack of a full, three inverse interferometer pseudostar flight system test is mitigated by the ability to perform the science in a reduced throughput mode with only two interferometers (one guide star interferometer and one science interferometer) constrained to operate in a planar configuration

Shared Baseline Flight System Test Approach Substantially More Robust Than Reference Design Approach

Calibration Approach

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- SIM is not an ideal interferometer. Many nanometer-class effects are present:
  - Diffraction: difference in path between starlight, metrology, and a ray passing through the system.
  - Polarization: mostly in metrology, false pathlength reading due to polarization changes as corner cubes articulate
  - Beam Walk: tilt of siderostats, dihedral errors on rotating corner cubes
  - Time-dependent terms: beam walk, changing optical figure, other.
    - These are specified in the error budget to remain below some tolerable level.
- Error budget allows:
  - ~ 200 pm r.m.s. for uncalibrated errors in wide-angle astrometry.
  - ~ 10 pm r.m.s. for uncalibrated systematic errors in narrow-angle astrometry.
- Calibration is a critical function and two complementary approaches are being evaluated in parallel:
  - External: looking at stars
  - Internal: derived from on-board light sources and redundancy

Calibration Function

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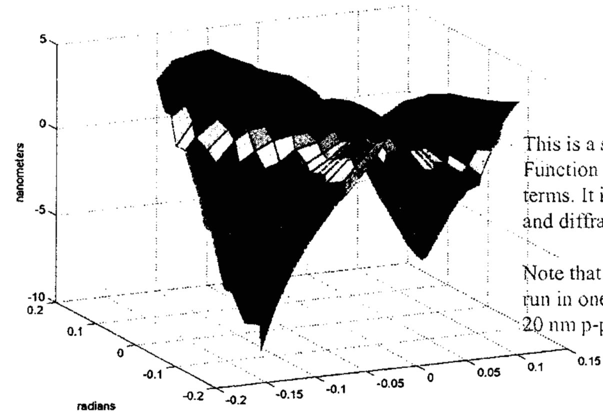
delay = <b,s> + c + n

c = c(u,v) = systematic delay error = calibration function

n = noise

Non-linear portion of "true" calibration function



This is a sample calibration Function after removal of linear terms. It includes polarization and diffraction.

Note that diffraction oscillations run in one direction.
20 nm p-p due mostly to polarization.

External Calibration

- Observe a field of stars, determine calibration using the instrument more-or-less as it is used to make standard observations.
- Technique:
  - Canting/rolling: observe the difference in position of the stars at two different s/c orientations.
    - Insensitive to true star positions at 2 mas.
- Wide-angle:
  - The calibration techniques on a single tile (15 deg) do not identify baseline orientation and length. This comes from grid measurements.
- Narrow angle:
  - No significant contribution to measured calibration function from length and orientation.

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Internal Calibration

- C(u,v) is caused by articulation in three and only 3 imperfect optical elements
  - (2) Siderostats (and CC embedded in siderostat)
  - (1) Delay line
- Internal sources and sensors are built into SIM for on orbit internal cal.
  - Siderostat retro-mode calibrates diffraction and internal-path beam walk.
    - Measures difference between full-aperture beam and metrology beam.
  - External metrology redundancy calibrates polarization and corner cube dihedral effects.
    - 4 beams incident on articulating corner cube, these beams allow determination of polarization and dihedral parameters.
- Advantage of internal calibration
  - No shot noise
  - Faster calibration allowing more frequent calibration cycles.
- Validation
  - Internal calibration is validated by observing a field of stars at different orientations and obtaining the same relative star separations.

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Calibration Summary

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- External Calibration
  - We have a good understanding of how to calibrate the delay measurements within a tile.
  - We still have to prove that we can calibrate the baseline orientation in different tiles.
  - Our conclusions are predicated on modeling of the diffraction and other effects.
    - Our testbed program is needed to verify the models.
- Internal Calibration
  - The sources and sensors for on orbit internal calibration are designed into SIM.
  - Validation of internal calibration can be performed in the technology program, (MAM-1, MAM-2/3) as well as on the SIM flight hardware.

Substantial Progress Being Made Towards Understanding Shared Baseline Calibration Techniques

Shared Baseline Summary

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- Maximum science
  - best throughput for planet finding
  - retains wide angle astrometry
- Simpler / less risk than SIM-Classic
  - less metrology
  - no switchyard
  - fewer deployments (PSS & metrology boom)
  - no metrology kite
- Minimal new technology to be demonstrated
- End to end two interferometer flight system astrometric performance test now possible (single interferometer only test proposed for SIM-Classic)
- Significant progress understanding internal and external calibration approaches

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External Review Board
SIM Risk & Reliability Assessment

22 & 23 March 2001

Risk/Reliability/Redundancy Assessment Team
- Jim Arnett
- John Walker
- Kim Aaron
- George Fox
- Peter Kahn
- Michael Wehner

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Risk Management Overview

- **SIM Risk Management Approach**
  - **Single Point Failure Policy applied across design processes**
  - **Risk Management Plan Preliminary Release: 03/06/2000**
  - **Significant Risk List Development**
    - **Risk Identification Check List Developed**
    - **Project Level initial set of risks identified and rated**
    - **Preliminary Risk Identification workshops for design options held with Subsystem Leads/Project Element Managers**
  - **Risk Mitigation Planning**
- **Design Concepts Redundancy/Reliability Assessment Approach**
- **Complexity/Risk Reduction Features of Shared Baseline**
- **IA Team Reference DesignRisk Assessment Issues vs. Shared Baseline**
- **Reliability Models for SB & ParaSIM**
- **Risk Summary**
- **Key Question #2 answered**
- **Backup charts include IA summary and reliability model details**

Reliability/Redundancy Approach

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- Single Point Failure Policy (SPF) drives redundancy trades
- Some SPF exemptions identified
  - Common: Structure, Solar Array, High Gain Antenna
  - Design-Specific: Metrology Boom (SB), Sid Mirrors (SB), Corner Cubes (Sonata)
- Criticality of design specific accepted SPF exemptions requires special efforts to provide highest possible reliability within project resources by elimination of causes of failure based on physics
- Specific attention wrt reliability/redundancy issues given to Concerns/Issues identified by the NASA Independent Assessment Team with major items addressed by new designs
- Block redundancy has been assumed for Design Variation costing studies
  - "Blocks" are at highest level (e.g., interferometer)
    - Lower level interdependencies to be approached later
  - Other functional, reliability approaches will be investigated
    - May lead to variations on selected design option
- Risk Management Approach is being applied to the selected design
  - Significant Risk List defines risk source, likelihood of occurrence, consequences
  - Probabilistic Risk Analysis (PRA) Fault Tree Analysis and FMECAs will support identification of sources of risk and potential failure modes
  - Preliminary Reliability Models already being developed for SB & Parasim
  - Use of functional vs. block redundancy will be evaluated for selected design

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SIM Risk Identification & Ranking Checklist

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- Identifying Risks: Ask "What can go wrong with my Plan?" The Answer is a RISK!
  - Programmatic considerations
    - **e.g. Launch vehicle availability, other Programs' results or failures**
  - Political considerations
    - **e.g. Changes in NASA budgets, Level of Advocacy maintained**
  - Technical & development considerations
    - **e.g. Technology not ready?, Software development problems, testbed failures**
  - Mission Risks
    - **e.g.,What can go wrong in flight?, DSN impacts, on-orbit calibration, descopes**
- Risk ratings defined:
  - Likelihood: Negligible, Low, Significant, High
  - Consequences(Impacts): Negligible, Low, Significant, High
- Prevention:
  - Mitigation recommendation development/implementation process in place
- Tracking: On-line Significant Risk List Tool

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Mitigation of Reference Design Risks by New Design Concepts

- Features that reduce risk
  - Monolithic Structure for all designs
    - Eliminates Deployment concerns
    - Eliminates microdynamics concerns with hinges and latches
  - External Metrology reduction for all designs
    - Significantly reduces complexity by eliminating Metrology Kite
      - Beam launchers, mK Thermal, Deployments, Mechanisms, etc.
    - Boom Simplified (Shared Baseline)
      - 1.0 M vs. 9 Meter with 4 arms
      - Single deployment
    - Boom eliminated (ParaSIM and Sonata)
  - Significant reduction in total #'s of mechanisms
  - Simplified Optics
    - On-axis TMA design with Flight heritage
    - Fewer Siderostats in all designs
    - Switchyard elimination
  - On-Orbit Graceful Degradation for each design provided
  - Shuttle Launch more benign environment/Availability highly likely

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Design Concept Features Still Requiring Risk Mitigation

- Some Features that will require special attention to reduce risk:
  - Shared Siderostats
    - Common to two interferometers
    - Some electronic and/or electromechanical failure modes create SB SPF
    - Careful design of Fault Containment regions help mitigate risk & reduce complexity
  - Front-Back Double Corner Cubes with Cutouts
    - Mounting to Siderostat & Knowledge of vertex
      - Plan to address in MAM-2

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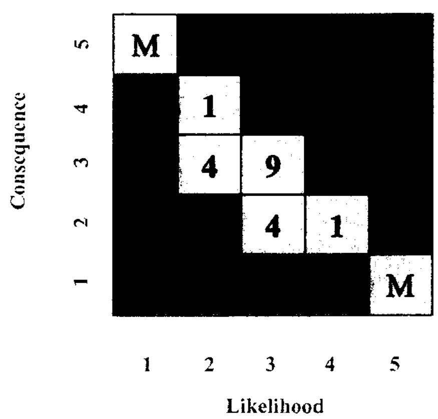
NASA Independent Assessment Team Risk Items & Open Issues Addressed

- IA Final Report identified 40 Risk issues
- Project has completed responses and closures to 37 Risk issues
- IA Team specifically identified 11 key design & requirement related risks in the following areas:
  - Nulling requirements
  - Imaging requirements
  - Complexity of the Switchyard
  - External Boom/metrology risks
  - Effects of Beam Walk on Metrology
- New design concepts eliminated or mitigated all of these 11 key risks
  - See risk issues now hi-lighted as GREEN in following charts
- Project provided responses including analysis, planning or Req'ts changes that closed 26 other issues with forward action (Hi-lighted as BLUE in following charts)
- IA team is reviewing the Design Concepts to develop revised independent risk assessment of SIM Project's recommended design option and risk mitigation

Initial IA Team Risk Rating Issues for Reference Design

- Conversion table for risk ratings
  - H: High - 10
  - H: Moderate - 19
  - L: Low - 11



Original IA Risk Issues for Reference Design Addressed by Design Concepts - High Risk

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Risk Item	LxC	status
[redacted]	[redacted]	[redacted]
Incomplete contamination requirements	4 x 4	[redacted]
[redacted]	[redacted]	[redacted]
Diffraction and Polarization Effects in Metrology	4 x 3	[redacted]
Lack of detailed verification plan for nanometer stability	3 x 4	[redacted]
[redacted]	[redacted]	[redacted]
Temperature Changes on Beam Launcher Beam Splitters	3 x 4	[redacted]
Thermal development tests need to be planned and budgeted	3 x 4	[redacted]

*wfa = "with forward action planned"

Original IA Risk Issues for Reference Design Addressed by Design Concepts - Moderate Risk

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Risk Item	LxC	status
Contamination of Field Stop	3 x 3	[redacted]
Impact of Autonomy on ISC Requirements	3 x 3	Open, info?
ISC Software Management	3 x 3	[redacted]
Definition of Design Margin for Nanometer Stability	3 x 3	[redacted]
[redacted]	[redacted]	[redacted]
PZT fatigue	3 x 3	[redacted]
SCI Data Bus Maturity	3 x 3	[redacted]
Software Reuse Planning for Ground Science Processing	3 x 3	[redacted]
[redacted]	[redacted]	[redacted]
Contamination Effects on Throughput	4 x 2	[redacted]
Heater panel temperature stability	2 x 4	[redacted]

Original IA Risk Issues for Reference Design Addressed by Design Concepts - Low Risk

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Risk Item	LxC	Status
[redacted]		
Optical Surface Quality	3 x 2	[redacted]
Siderostat Gimbal Encoder	3 x 2	[redacted]
[redacted]		
Lack of a long term straw-man Mission Scenario or "Design Reference Mission"	2 x 3	[redacted]
Proportional vs thermostatic control of heaters	2 x 3	[redacted]
[redacted]		
Completeness of the Wavefront Error Budget	2 x 2	[redacted]
Deferral of spacecraft requirements flowdown	2 x 2	[redacted]
Validity of thermal modeling assumptions	2 x 2	[redacted]

Original IA Risk Issues for Reference Design Addressed by Design Concepts - Low Risk

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Risk Item	LxC	Status
Dim/Science Stars Tracking	2 x 1	[redacted]
Orbit Selection	2 x 1	[redacted]
Managing the transition to a flight project	N/A	[redacted]
[redacted]		
Schedule for Technology Development Relative to Flight System Development	N/A	[redacted]
Size of Field Stop	N/A	[redacted]
Sun Exclusion Angle	N/A	[redacted]

Proposed Project Changes to IA Ratings Based on Design Concepts & Planned Mitigation

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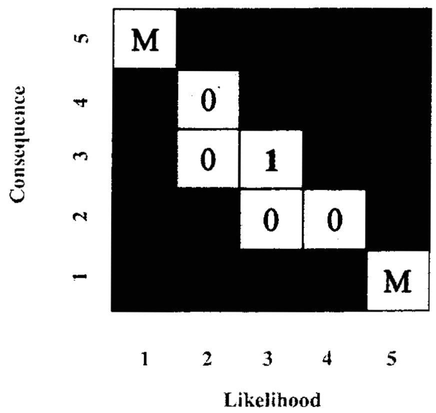
- Remaining risk issues:
  - H: High - 2
  - M: Moderate - 1
  - L: Low - 0

- **# Closed by New System Design Concepts - 11**
- # Closed by Planned Technology Tasks - 5
- # Closed by Analysis or Test Data to IA - 9
- # Closed by Requirement Clarification update - 8
- # Closed by IA Team Review - 4



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Mission Reliability Modeling Approach

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- Focus only on elements that are different for the two preferred designs
- Represent both designs as combinations of the following seven blocks:
  - Metrology Sources, Beam Combiners, Pallet Articulation Mechanisms, Telescopes, Siderostats, Beam Launchers, Front-End Electronics.
- Specify distribution function† for probability that each block fails at some point during the mission.
- Specify logical dependences between blocks for each system design.
- Use distribution functions to construct a set of go/no-go outcomes for each block & use dependencies to infer corresponding outcome for the two system designs.
- Repeat many times (20,000 samples here)
- Use outcome statistics to compute system failure probabilities
- Evaluate sensitivity of System Level failure probabilities to component failure

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†We used fixed probabilities (ie distribution is a step). MCTOOL supports use of many common distributions.

Blocks in Reliability Model

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Most Reliable → Least Reliable

Reliability Block	Contents	Rationale
Front-End Electronics	I/O, Power Conditioning & Cabling for Pallet Articulation Mechanisms, Telescopes, Siderostats, Beam Launchers	small part count, no moving parts, good high rel heritage for this kind o function
Pallet Articulation Mechanism	Actuators, Mechanisms, Drive Electronics	small parts count, simple mechanism less reliable than electronics because of moving parts
Siderostat	Mirrors, Gimbal Mechanisms, Corner Cubes, Thermal Control, Structure, Drive Electronics	more complex mechanism than #2, but use internal redundancy (encoders, motor wdgs etc) to limit pFail
Telescope	TMA, Fast Steering Mirror, Quad Cells, Thermal Control, Structure, Drive Electronics	fewer moving parts than siderostat, but more delicate, more functions an no internal redundancy
Metrology Source†	Laser Sources, Frequency Shifter, Frequency Modulator, Fiber Distribution System, Therma Control, Structure, I/O & Power Supply Electronics, Cabling	complicated, new technology, high risk of latent failure modes
Beam Launcher	Optics, Detectors, Dither Mechanisms, Therm Control, Structure, Drive Electronics	complicated, new technology, high risk of latent failure modes, less proven heritage than met source
Beam Combiner	Delay Lines, Fringe & Angle Cameras, Interna Metrology Beam Launchers, Flight Computers I/O Network, Thermal Control, Structure, I/O & Power Supply Electronics, Cabling	very complex, large no of components, high risk of latent failur modes

†Metrology Source is included for completeness. It is assumed to be the same in both designs and is not included in the reliability model.

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Sensitivity of System Reliability to Component Reliability

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- Reliability of Pallet Articulation Mechanism is not a significant discriminator
- ParaSIM is much less sensitive to failures in Front-End Electronics and Siderostats than Shared Baseline, and marginally less sensitive to failures in Telescopes and Beam Combiners.
- Shared Baseline is marginally less sensitive to Beam Launcher failures than ParaSIM.

Reliability Block	Sensitivity of System pFail to Block pFail
Front End Electronics	**Parasim**
Pallet Mechanism	–
Siderostat	**Parasim**
Telescope	Parasim
Beam Launcher	Shared Baseline
Beam Combiner	Parasim

Legend

– No Discriminator
Marginally Less Sensitive
Much Less Sensitive

Conclusion

On balance, when the costed versions of the two designs are compared, Parasim is less sensitive to failure than Shared Baseline.

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Risk/Reliability Summary

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- IATeam's design specific complexity and risk concerns based on Reference Design have been largely reduced by new concepts, especially in optical design area
- Project's Technical Advisory Committee (SIMTAC) has affirmed that complexity and risk of new designs are comparable to other successfully missions
- ParaSIM is more robust than Shared Baseline with respect to system mission reliability:
  - Key component technology development to improve Beam Launchers and Beam Combiners will make reliability less of a discriminator between the designs
- Shared Baseline & ParaSIM both degrade gracefully with component failures

Conclusion:

- Both design options have an acceptable level of development and mission risk with significantly reduced complexity

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Five Key Questions

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1. Does SIM fit in the larger framework of other missions and other techniques? ***YES***
   - SIM does unique science that no other planned mission can/will do
   - TPF needs SIM (technology, target identification, planet masses)
2. Is SIM feasible from an engineering and technology perspective? ***YES***
   - **SIM new design is much less complex and risky than the Reference Design, and is now no more complex than missions that have successfully flown (per the SIMTAC)**
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap? ***YES***
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets? ***NO***
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry? ***YES***
   - This capability allows SIM to detect long-period (>5 year) planets necessary for TPF
   - Global Astrometry is a key science capability endorsed by the Decadal Reports

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Backup Charts

IA Risk Assessment & Findings Process

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Findings

- IA findings comprise:
  - Overall assessment of the state of the project
  - Specific issues that require Project action
  - Independent cost estimates
- All findings discussed with the Project
  - Watch Forms, TIMs, presentations
- Program-level risk assessment based on:
  - Comparison to state-of-the-art
    - Number of enabling technologies required
    - How far beyond state-of-the-art
  - Comparison to other Space Science programs
    - Technology maturity
    - Design, integration and test complexity
  - Combination of likelihood that desired performance, cost, or schedules will be achieved and impact of not achieving them

Issues

- IA Issues
  - Concerns where IA Team recommends actions in addition, or contrary, to planned actions
  - Documented and tracked via "watch forms"
- Grouped into 4 categories
  - Requirements
  - Technology
  - Design, Development, Test, and Evaluation (DDT&E)
  - Project Management
- Likelihood and consequence of each issue rated
  - Utilized a modified hazard analysis technique
    - Assessed likelihood that each issue will be realized
    - Characterized consequence as technology immaturity, design modification, process change, and/or cost impact
- Converted ratings to one dimension to capture risk "magnitude"

IA Team Risk Ratings for Reference Design Issues

LIKELIHOOD

Rating:	What is the likelihood that the concern will be realized with the existing approach?
5) Certain	Current approach cannot prevent the event, and there are no alternatives available.
4) Extremely likely	Current approach cannot prevent the event, but there is an alternative available.
3) Likely	Current approach can prevent the event, but additional action is necessary.
2) Unlikely	Current approach is usually sufficient to prevent the event.
1) Extremely unlikely	Current approach is sufficient to prevent the event.

CONSEQUENCE - TECHNOLOGY

Rating:	What is the consequence of not addressing the stated issue?
5) Unacceptable	Issue could make this technology impossible
4) Major maturity reduction	Technology will attain TRL of 2 by NAR
3) Moderate maturity reduction	Technology will attain TRL of 3 by NAR
2) Minimal maturity reduction	Technology will attain TRL of 4 by NAR
1) No appreciable impact	Technology will attain TRL of 5 (Required for NAR)

IA Team Risk Ratings for Reference Design Issues

Space Interferometry Mission

CONSEQUENCE - DESIGN

Rating:	What is the consequence of not addressing the stated issue?
5) Unacceptable	Can not meet mission requirements, and no alternatives exist
4) Major redesign required	Can not meet mission requirements, major redesign required
3) Moderate redesign required	Can not meet mission requirements, moderate redesign required
2) Minor redesign required	May not meet mission requirements, minor redesign required
1) Minimal impact	Requirements met, but issue may produce some degradation

CONSEQUENCE - PROCESS

Rating:	What is the consequence of maintaining the current process?
5) Unacceptable	Current process can not accomplish the intended goals.
4) Significant difficulties	Current process will lead to difficulty in accomplishing the intended goals.
3) Moderate difficulties	Current process will lead to some difficulty in accomplishing the intended goals.
2) Minor difficulties	Current process will lead to minor difficulty in accomplishing the intended goals.
1) Minimal Impact	Current process will have no appreciable impact.

CONSEQUENCE - COST

Rating:	What is the consequence of not addressing the stated issue?
5) Unacceptable	Budget increase > 25%
4) Major impact	Budget increase > 15%
3) Moderate impact	Budget increase > 10%
2) Minimal impact	Budget increase > 5%
1) No appreciable impact	Budget increase < 5%

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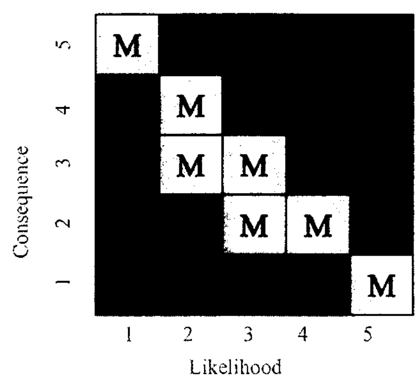
IA Risk Summary (LxC) Chart

Space Interferometry Mission

- Conversion table for risk ratings
  - H: High
  - M: Moderate
  - L: Low



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Space Interferometry Mission

Mission Reliability Model/Analysis

BACKUP CHARTS

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Mission Reliability Modeling Approach

- Focus only on elements that are different for the two preferred designs
- Represent both designs as combinations of the following seven blocks:
  - Metrology Sources, Beam Combiners, Pallet Articulation Mechanisms, Telescopes, Siderostats, Beam Launchers, Front-End Electronics.
- Specify distribution function† for probability that each block fails at some point during the mission.
- Specify logical dependences between blocks for each system design.
- Use distribution functions to construct a set of go/no-go outcomes for each block & use dependencies to infer corresponding outcome for the two system designs.
- Repeat many times (20,000 samples here)
- Use outcome statistics to compute system failure probabilities
- Evaluate sensitivity of System Level failure probabilities to component

†We used fixed probabilities (ie distribution is a step). MCTOOL supports use of many common distributions.

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Assumptions Common to Both Designs

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- No significant discriminators in Spacecraft or Metrology Source
- Beam Combiner modeled as a single block
- Failure probability of each block is the same in both designs.
- Siderostats are mounted on 2 articulated pallets: 1 & 2.
  Each pallet has two rotational degrees of freedom: X and Y
  Mission Success => (X1 .OR. X2) .AND. (Y1 .OR. Y2) = GOOD
- In each Siderostat Bay, "Front End Electronics" (i/o, power & cabling) is in series with local Siderostat, Telescope, Beam Launcher(s), Pallet Actuator

Assumptions for Shared Baseline

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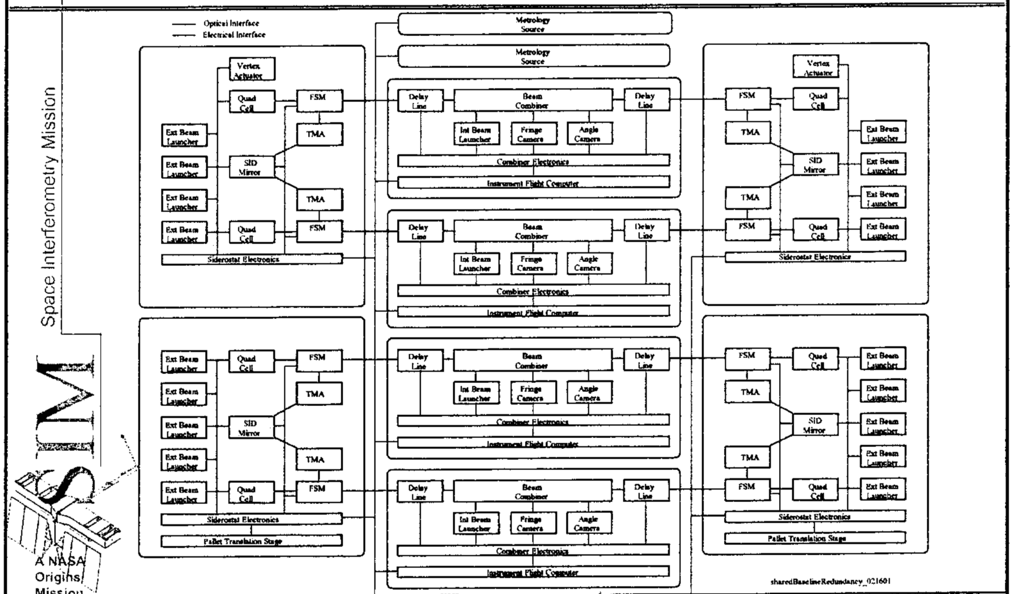
- 4 Siderostats: 2 per pallet
- 8 Telescopes: 2 per Siderostat:
  Siderostat BAD => both associated telescopes BAD
- 4 Beam Combiners: 1 per left-right telescope pair
- 4 Baselines: Beam Combiner .AND. Telescope Pair
  Beam Combiner or either Telescope BAD => associated Baseline BAD
- 18 Beam Launchers: 2 on each edge of pyramid + 2 on one base diagonal
  Metrology System Working => At least one Launcher on each edge is working.
- 4 Interferometers: Baseline .AND. Metrology System
  Metrology System BAD => all 4 Interferometers BAD
- Working Instrument => At least 3 Interferometers are GOOD

shared baseline block diagram



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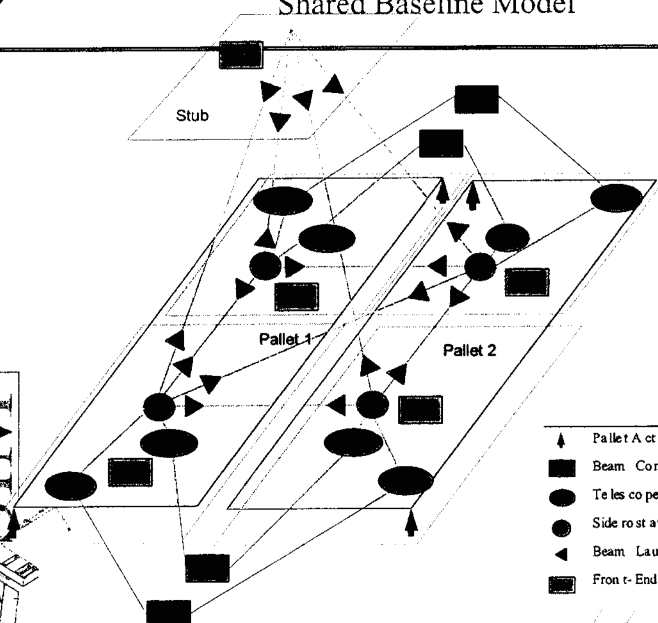
Shared Baseline Model



	Para Sim	Shared Baseline
Pallet Actuator	4	4
Beam Combiner	3	4
Telescope	6	8
Siderostat	6	4
Beam Launcher	10	18
Front-End Electronics	6	5

Space Interferometry Mission

SIM

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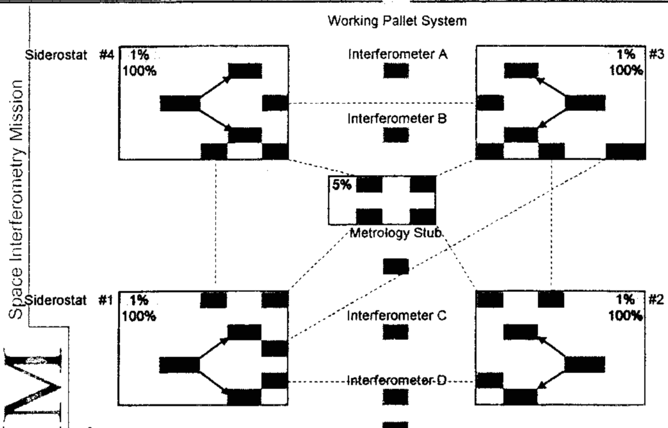
Reliability Model for Shared Baseline Sensitivity to Single Failures

Shared Baseline SIM

Space Interferometry Mission



Percentages in colored boxes indicate pFail for system when pFail for corresponding component is 1.

Working Instrument:
3 of 4 Interferometers Working

pFail		
Front End Electronics		0.0003
Stub Electronics		0.0003
Pallet Actuator		0.0005
Siderostat		0.001
Telescope		0.003
Beam Launcher		0.01
Beam Combiner		0.03

Legend	
Metrology System	
Working Instrument	

Fault Containment Region

SIM
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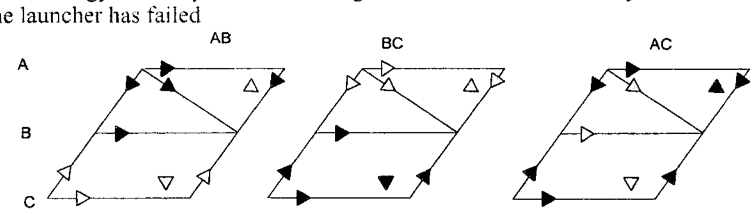
Assumptions for ParaSIM

Space Interferometry Mission

- 6 Siderostats: 3 per pallet.
- 6 Telescopes: 1 per Siderostat:
  Siderostat BAD => associated telescope BAD
- 3 Beam Combiners: 1 per left-right telescope pair
- 3 Baselines: Beam Combiner .AND. Telescope Pair
  Beam Combiner or either Telescope BAD => Baseline BAD
- 10 Beam Launchers
- 13 Metrology Sets: any of the following three minimal sets .OR. any set in which only one launcher has failed



- 3 possible Interferometer Pairs: AB, BC, AC
  Interferometer Pair = 2 Baselines .AND. Metrology Set
- Working Instrument => at least one Interferometer Pair is GOOD

SIM
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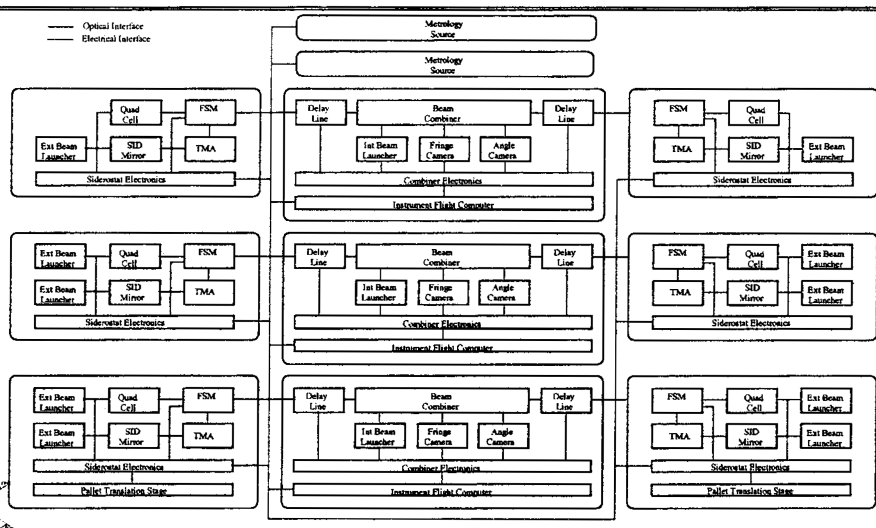
ParaSIM block diagram



Space Interferometry Mission

SIM

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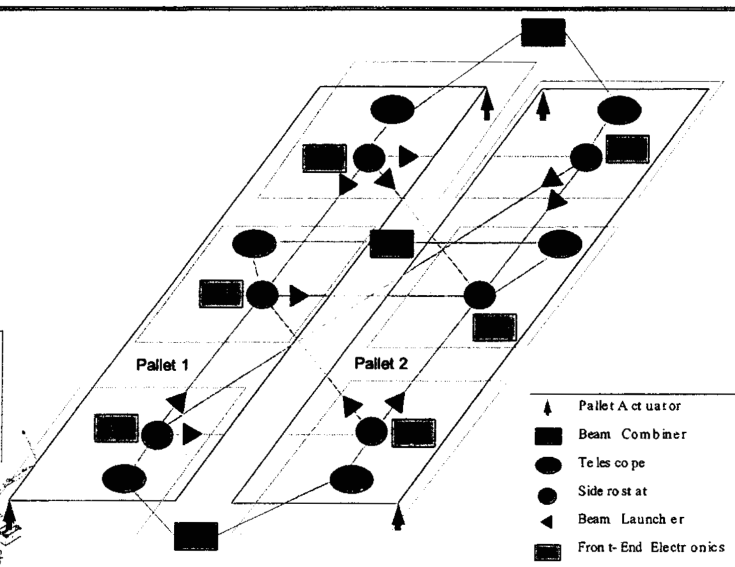
ParaSIM Model



	Para Sim	Shared Baseline
Pallet Actuator	4	4
Beam Combiner	3	4
Telescope	6	8
Siderostat	6	4
Beam Launcher	10	18
Front-End Electronics	6	5

Fault Containment Region

Space Interferometry Mission

SIM

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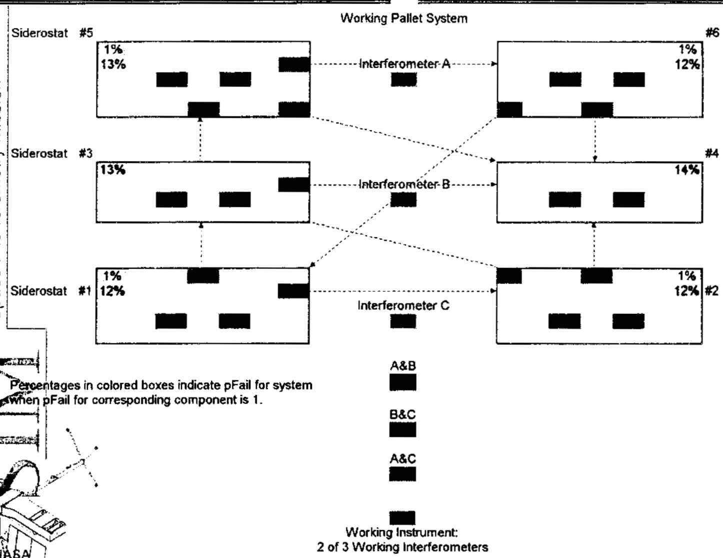
Reliability Model for ParaSIM Sensitivity to Single Failures

Parasim



pFail	
Front End Electronics	0.0003
Pallet Actuator	0.0005
Siderostat	0.001
Telescope	0.003
Beam Launcher	0.01
Beam Combiner	0.03

Legend

Interferometer Pair Working Instrument

Fault Containment Region

Space Interferometry Mission

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Sensitivity of System Reliability to Component Reliability

- Monte Carlo Tool was used to assess sensitivity of System Failure probability to each block failure probability for all six blocks in both designs.
- System Failure probability was computed with each block failure probability at six discrete values while block failure probability for the other 5 blocks was set to zero.

Space Interferometry Mission

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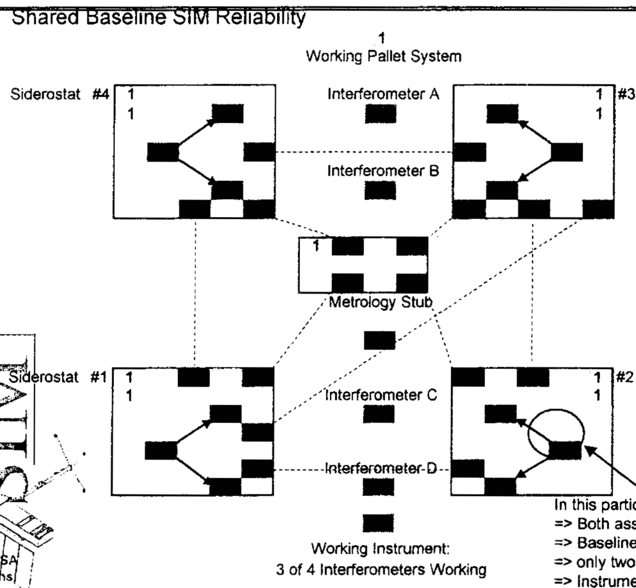
Shared Baseline Model Example Analysis

Space Interferometry Mission

Shared Baseline SIM Reliability



sample values for illustration only

pFail

Front End Electronics		0.0003
Stub Electronics		0.0003
Pallet Actuator		0.0005
Siderostat		0.001
Telescope		0.003
Beam Launcher		0.01
Beam Combiner		0.03

Legend

Metrology System

Working Instrument

Fault Containment Region

Note: pFail represents the probability that the block will fail at some point during the mission. These are nominal values chosen purely to provide a starting point for analyzing the sensitivity of Parasim and Shared Baseline to the reliability of each block.

In this particular trial, Siderostat #2 has failed
=> Both associated Telescopes are Bad
=> Baselines C and D are BAD
=> only two working Interferometers
=> Instrument is BAD

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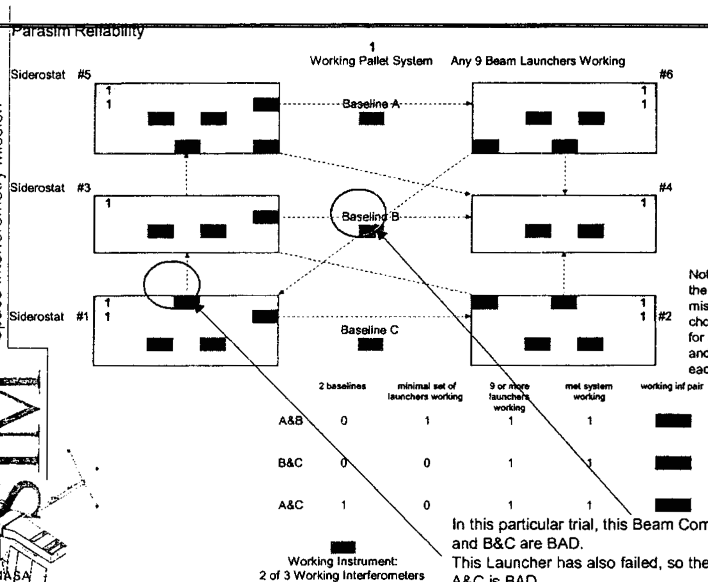
ParaSim Model Example Analysis

sample values for illustration only

Space Interferometry Mission

Parasim Reliability



pFail

Front End Electronics		0.0003
Pallet Actuator		0.0005
Siderostat		0.001
Telescope		0.003
Beam Launcher		0.01
Beam Combiner		0.03

Legend

Interferometer Pair

Working Instrument

Fault Containment Region

Note: pFail represents the probability that the block will fail at some point during the mission. These are nominal values chosen purely to provide a starting point for analyzing the sensitivity of Parasim and Shared Baseline to the reliability of each block.

In this particular trial, this Beam Combiner has failed => both A&B and B&C are BAD.
This Launcher has also failed, so the minimal set of 7 Launchers for A&C is BAD.
However, 9 Launchers are GOOD, so the MET system is GOOD.

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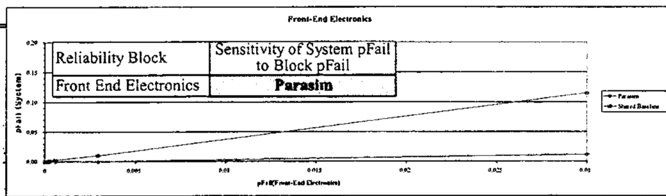
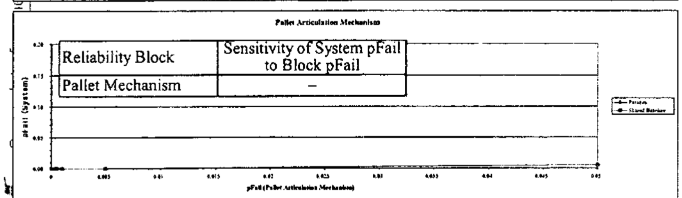
Sensitivity Analysis



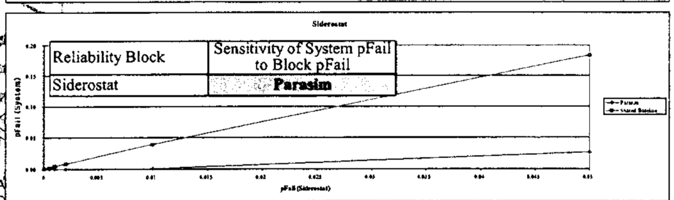
Front-End Electronics

pFail	pFail(System) Parasim	Shared Baseline
0	0.00000	0.00000
0.00015	0.00000	0.00030
0.0003	0.00000	0.00100
0.0006	0.00000	0.00265
0.003	0.00000	0.01070
0.03	0.01195	0.11490



Pallet Articulation Mechanism

pFail	pFail(System) Parasim	Shared Baseline
0	0.00000	0.00000
0.00025	0.00000	0.00000
0.0005	0.00000	0.00005
0.001	0.00005	0.00000
0.005	0.00000	0.00000
0.05	0.00500	0.00460

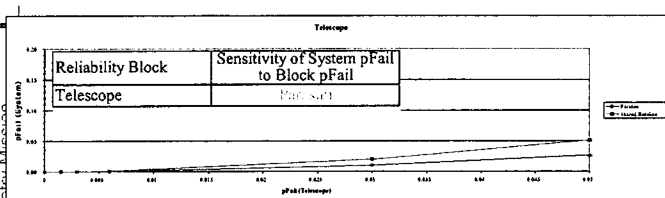


Siderostat

pFail	pFail(System) Parasim	Shared Baseline
0	0.00000	0.00000
0.0005	0.00000	0.00180
0.001	0.00000	0.00420
0.002	0.00015	0.00845
0.01	0.00105	0.03885
0.05	0.02570	0.18210

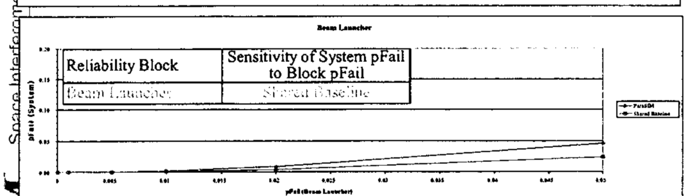
– No Discriminator
Marginally Better
A Lot Better

Sensitivity Analysis (Cont)



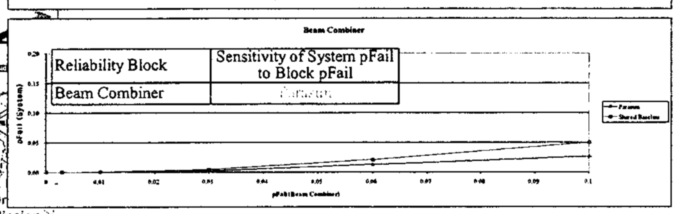
Telescope

pFail	pFail(System) Parasim	Shared Baseline
0	0.00000	0.00000
0.0015	0.00000	0.00005
0.003	0.00005	0.00020
0.006	0.00025	0.00105
0.03	0.01000	0.01940
0.05	0.02555	0.05025



Beam Launcher

pFail	pFail(System) Parasim	Shared Baseline
0	0.00000	0.00000
0.001	0.00005	0.00000
0.005	0.00070	0.00020
0.01	0.00170	0.00095
0.02	0.00800	0.00380
0.05	0.04515	0.02330



Beam Combiner

pFail	pFail(System) Parasim	Shared Baseline
0	0.00000	0.00000
0.003	0.00010	0.00005
0.01	0.00045	0.00060
0.03	0.00220	0.00465
0.06	0.01225	0.02055
0.1	0.02575	0.04935

– No Discriminator
Marginally Better
A Lot Better

NASA JPL

SIM Space Interferometry Mission
A NASA Origins Mission

External Review Board
Extra-Solar Planets: Discover, Diversity, and Characterization

S. R. Kulkarni
California Institute of Technology

23 March 2001

Current Situation: We Know Planets Exist

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1. Earth mass planets exist.
   Earths, Moon, and Asteroids around
   PSR 1257+12

2. Jupiter-mass objects around at least
   7% of nearby Sun-like stars.
   HD 209458 Occultation --> Jupiter size

3. Mass spectrum of brown dwarfs
   continues into the planetary regime.

In all cases, location and inferred masses in concordance with sensitivity of techniques.

Grey Clouds on the Horizon

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1. 47 Tuc: Deficit of RV Planets
   - 34000 stars surveyed
   - Expected 17 inner giants
   - None found

     ---> Low metallicity

     Crowded Neighborhood Dramatically Affected Evolution
2. Absence of planets around other millisecond pulsars.

What's Next?

SIM Space Interferometry Mission

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Goals:

a. Understand Planet Formation and Evolution in its entirety
   - Establish Incidence and Diversity of Extra-solar planets
   - Understand Evolution of Planetary Systems
   - Map the Architecture of Planetary Systems

b. Search for Earth-like Planets around Sun-like stars
   - A prelude and a complement to TPF

We can entertain two hypothesis:

a. Planets are exceedingly common
   - Detections limited by sensitivity

b. Planets are rare

This uncertainty has been noted by the Decadal Report.

How Do We Make Progress Beyond Current (Detection) Era?

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A two-pronged attack.

- A comprehensive search of thousands of nearby stars (young stars, differing metallicity, binary stars, and white dwarfs)

  --> a broad survey with high precision

- Intensive observations of 250 stars optimized for Earth detections

  --> a deep search with extreme precision

Masses and Outer Planets

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Masses -- A fundamental parameter

- Needed for quantitative progress

Outer Planets -- Hard to find with RV techniques.

- May play a significant role in the evolution of inner planets

SIM can measure masses down to a few earth masses

SIM has unique sensitivity to outer planets (enhanced with a 10-year mission)

Why is SIM unique?

SIM Space Interferometry Mission
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No other mission has

- the mass sensitivity of SIM
- the target throughput of SIM
- the ability to measure unambiguous masses
- the precision to measure orbital parameters
- the sensitivity to outer planets

What should SIM retain?

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- Mass sensitivity
  - 5 earths
- high target throughput
  - broad survey of ~2000 nearby stars
  - deep survey of ~250 nearby stars
- fidelity in measuring accelerations
  - this needs wide angle astrometry

SIM and Other Missions

SIM Space Interferometry Mission

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- FAME -- high throughput, low sensitivity
- Microlensing -- limited choice of targets, no follow up
- Keck Interferometer -- a highly restricted target list
- GAIA -- Very high throughput, moderate sensitivity
  - poor visit frequency
- Kepler -- high target throughput, complementary to SIM (size)
  - but follow up is highly limited
  - target diversity is limited (c.f Young stars)
- ECLIPSE -- highly complementary to SIM
  - outer planets (Jupiters, >3AU at 10pc)
  - size but no masses

SIM and TPF

SIM Space Interferometry Mission

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SIM is complementary to TPF.

- SIM measures masses. No other mission can do this.
- TPF measures sizes (albedo).
- SIM has no risk with zodiacal dust.
- SIM serves as pathfinder to TPF.
- SIM jump starts TPF.

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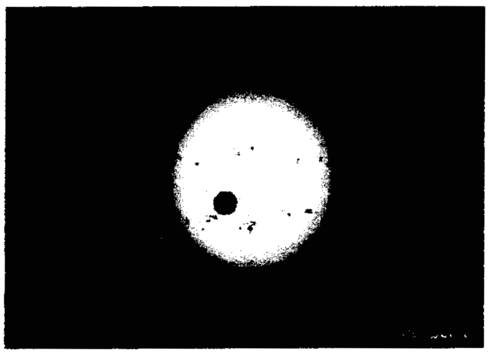
External Review Board
The SIM Planet Program



Mike Shao
Geoff Marcy
Chas Beichman

22 March 2001

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Current Knowledge of Extrasolar Planets

- Giant- Planet Occurrence: 7%
- More Small Masses U $1 M_{Sat}$
- Eccentric Orbits Common: Scattering?
- Multiple Systems of Giant Planets

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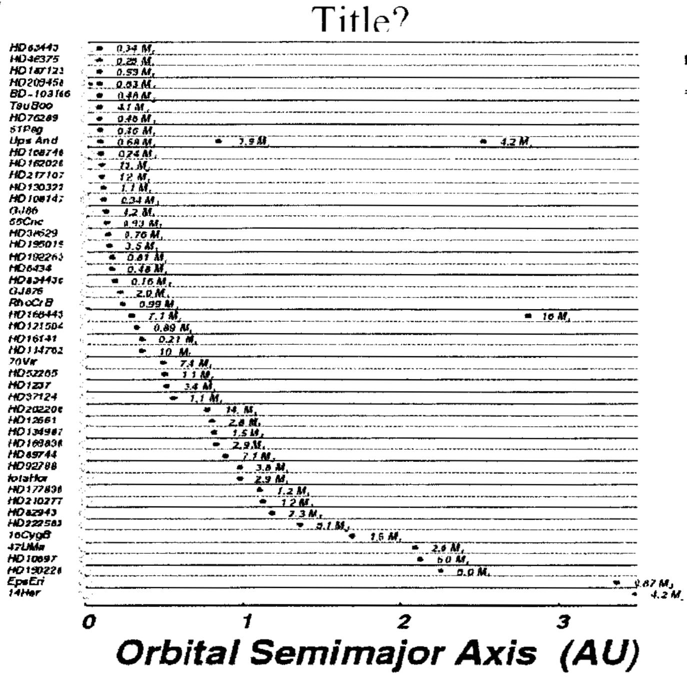
Title?



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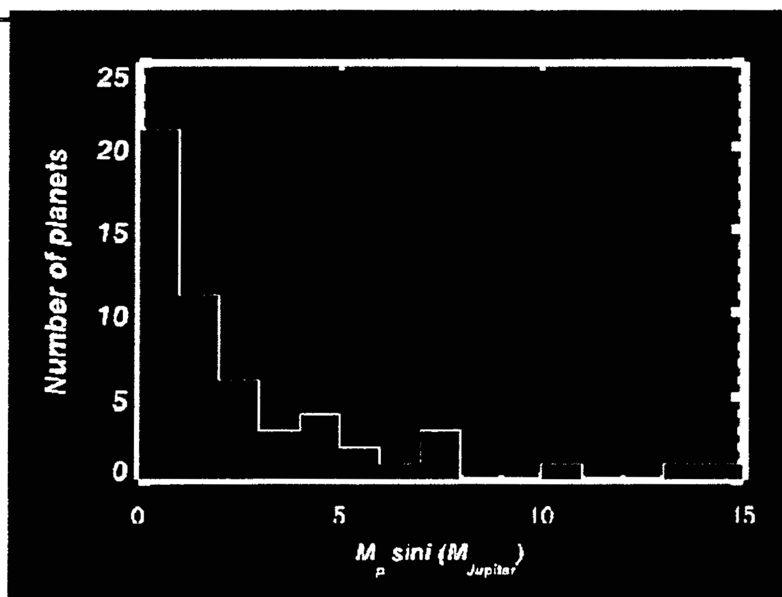
Mass distribution from Doppler Observations



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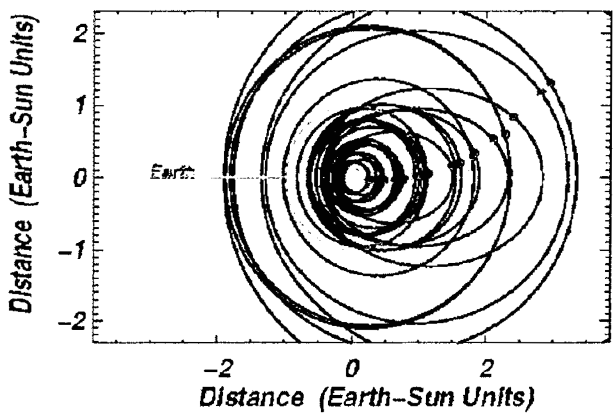
Eccentricities



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Current Ignorance of Extrasolar Planets

- Existence of Terrestrial Planets
- Planetary System Architecture
- Mass Distribution
- Eccentricities?
- Habitable Zone

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Planetary Characterization: Unique Contributions of SIM

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- First Terrestrial Planets (30 pc)
- Masses, Earths & Giant Planets
- Planetary Systems, Architecture
- Masses of Known Planets
- Reconnaissance for TPF

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Tier 1
1 μas precision

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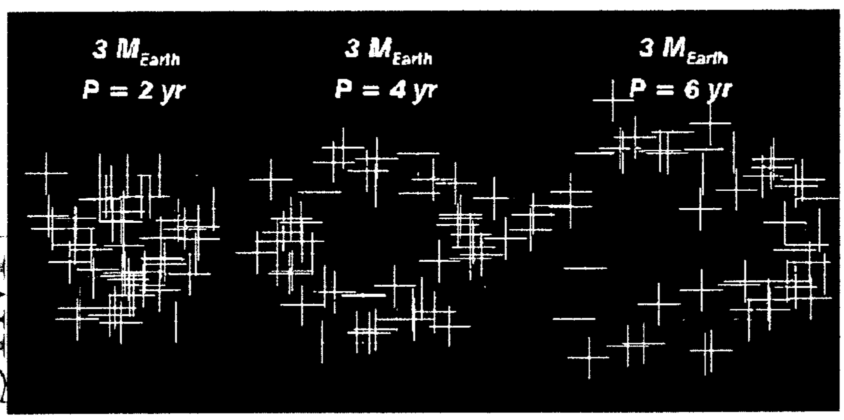
Detection of terrestrial planets around < 5pc stars



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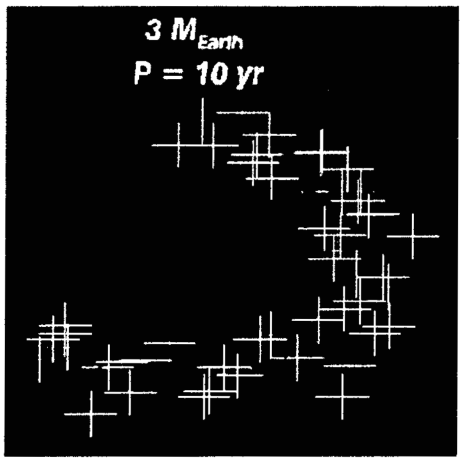
Tier 1 (cont'd)
1 μas precision

Long Orbital Periods



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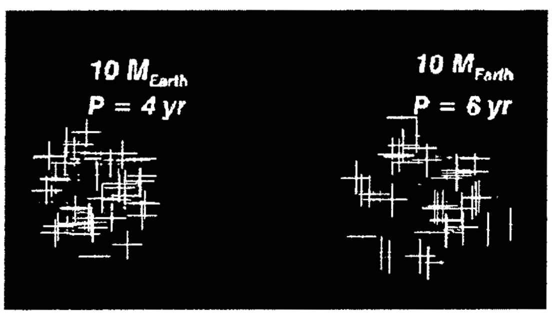
Tier 2
4 μas precision

Detection of terrestrial planets around ~10pc stars



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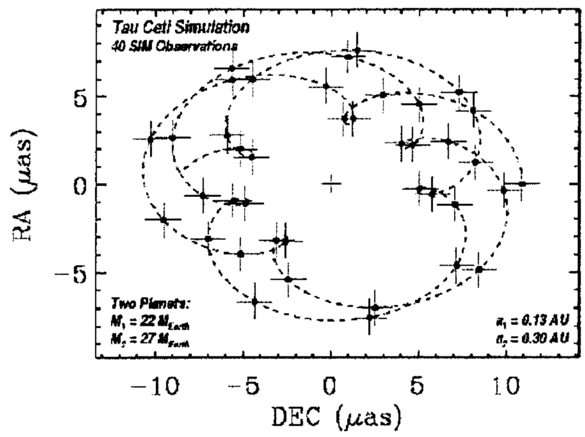
Tau Ceti: A Simulation

SIM Space Interferometry Mission



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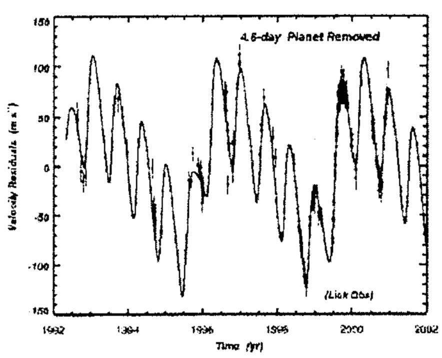
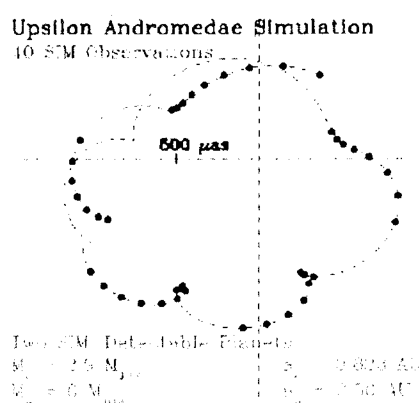
Investigate Co-planarity of Doppler- Detected Multiple Systems





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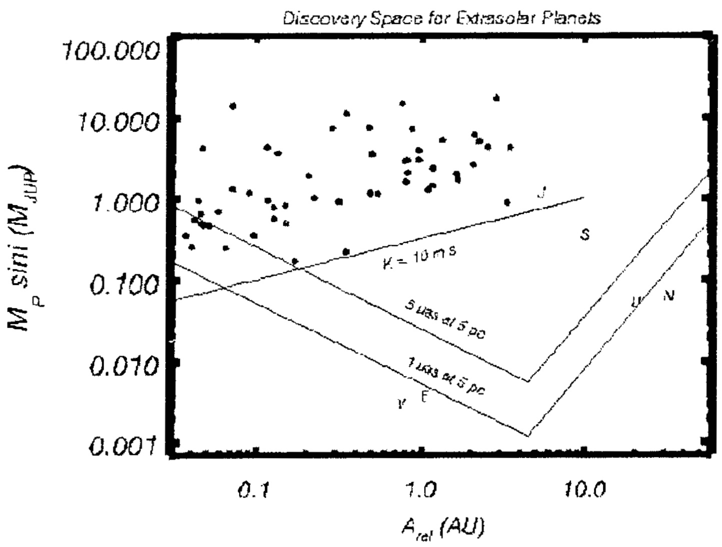
Discovery Space for Extrasolar Planets



Space Interferometry Mission

SIM

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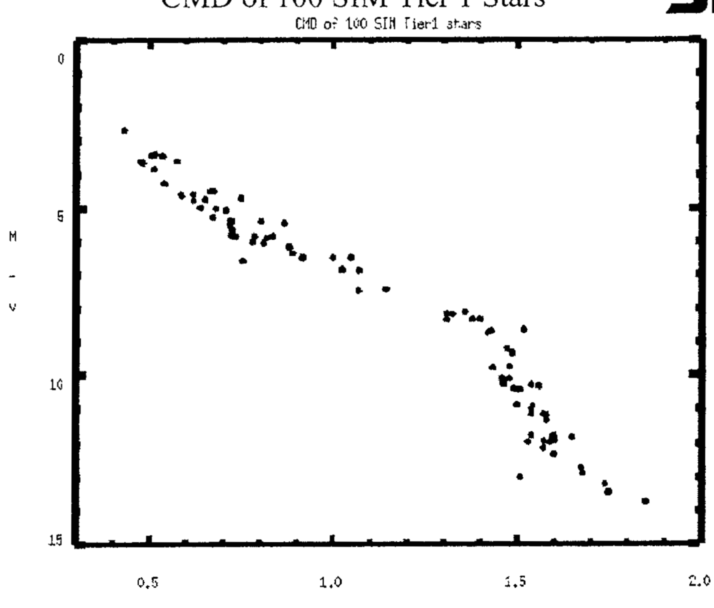
CMD of 100 SIM Tier 1 Stars



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TITLE?

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ERB Question
Planets Everywhere

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Factoids:

•The 1 uas single measurement error is ~ 50% variance photon noise

•Based on 10 mag star, 30 sec integration/visit

•The current scheme, of 5 ref stars, 1 target means:

•10 visits to the target (1 uas) (300 sec on target)

•2 visits for each ref star (2.2uas) (60 sec on each of 5 ref stars)

•Each epoch, measure x,y

•50 epochs, over 5 years (non-uniform time sampling to avoid aliasing)

Approach to separating which planet belongs to which star:

•pairwise comparisons

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Solving for Everything

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SIM Space Interferometry Mission

- Let's just look at the 5 ref stars to start (# unknowns vs # measurements)
  - 5*50*2 independent measurements, 100 independent measurements per star
  - We could try to solve for ~50 planetary terms. Each planet is described by 7 independent parameters, from the point of view of sqrt(N-fit), we could solve for 7 planets around each ref star and degrade our sqrt(N-fit) by roughly a factor of 2.
- Let's assume 7% of stars have a planet of 0.5 Jupiter mass or more and the density of planets grows as 1/M.
  - For a ref star at 100pc, 4AU radius, a planet with a mass of 1/40 of a Jupiter mass would produce a 1 uas amplitude motion.
  - If we accept 1/M density, there will be on the average 1.5 planets per star that are big enough to have a 1 uas signature.
- 1.5 planets is << 7 so we're ok.

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1Kpc vs 100pc Ref Objects

JPL

SIM Space Interferometry Mission

- There may be 1.5 planets per ref star at 100pc. At 1Kpc the planet mass has to be much larger, 1/4 Jupiter mass. ~ 15% of stars will have planets that matter.
- If we pick 3 ref stars (without stellar companions) there's a high probability that we'll find 2 w/o a planetary companion.
- However K giants @ 1 Kpc are 12~13 mag. And since at 10 mag 0.5 of the variance of our 1uas error is photon noise, the use of a 12 mag ref star has a significant impact on total integration time and/or final accuracy.
  - (could increase integration time on ref stars by 10x)
- Find ref stars in between 100pc and 1 Kpc.

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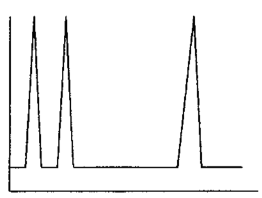
Resolution of Frequency Distribution

JPL

SIM Space Interferometry Mission

- With a 5 yr mission, we can resolve in the periodogram/equiv orbital frequencies different by 0.2 cycles/yr. 1 cycle/yr and 1.2 cycles/yr are separable.
  - 1 yr and 1.2 yr orbits could be resolvable



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Pairwise Comparisons
Which Planet Belongs to What Star

JPL

SIM Space Interferometry Mission

- With just N=2 stars, the problem is unsolvable.
- With N=3 stars, the problem begins to be solvable
- With N=4 or more stars, the problem becomes tractable even if two planets have similar orbital periods. As N grows the number of pairs grows as N^2 making the job easier.
- Given that planetary periods span very wide range of time scales and we have 0.2 cycle/yr resolution, this should be a tractable problem at N=4~5 ref stars.

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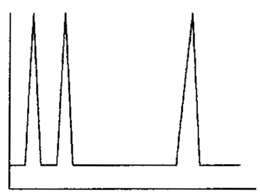
- A 1.4
- B 1.45, 0.9
- C 1.8
- D 2.1, 3.5

pairs	freqs					
A-B	1.4	1.45	0.9			
A-C	1.4			1.8		
B-C		1.45	0.9	1.8		
A-D	1.4				2.1	3.5
B-D		1.45	0.9		2.1	3.5
C-D				1.8	2.1	3.5



Long Period Planets
(First we need the Grid)

JPL

SIM Space Interferometry Mission

- All long period planets look alike, it's impossible using the previous technique to assign a long period planet to a particular star
- There's just an acceleration (in x and y)
- However if planets are somewhat like double stars, the planet density is roughly uniformly distributed in log period space
- The probability of a planet with a period > 5yrs, is ??? 50%. To find 2 stars with no long period planets (given 1.5 planets/star) means we need 4~5 ref stars.
  - (min)3.6 days= 0.01 yr, 5yr, 2500 yr (max period)
- This number number will be smaller for ref stars > 100pc. It may make sense just to go out to 200pc, but still 10 mag (F stars, Giants)

- This problem needs to be studied in much greater detail and all three planet key project will be looking at this issue. Multiple planets are to be expected.

If only 2 of 5 ref stars don't have acceleration, the whole "frame" will have a residual acceleration due to measurement noise that's ~sqrt(2) worse than if all the stars had no acceleration.

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Parallax and Planets

Space Interferometry Mission

SIM

•The parallax effect has a 1 yr period and fitting for the parallax can absorb planetary orbits within 0.2cy/yr of 1 cy/yr.

•Parallax however has a specific x,y signature depending on the location of the star wrt the ecliptic. Any component of a 1 yr period that doesn't fit that signature can be interpreted as a planet with a 1 yr period.

•The parallax effect is huge 100,000 uas for a star at 10pc, but its shape is know to 1uas if we know the position of the star to ~ 10urad (2 arcsec)

So even though it should be possible to detect a planet with a 1 yr period unless we're very unlucky and it only has an orbital component that matches the parallax effect, the orbital parameters will not be accurate. However, after the planet is detected by TPF and its orbital parameters measured with direct detection, SIM data should be able to deduce its mass.

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Global Astrometry with SIM

Stephen Unwin

Deputy Project Scientist

March 23, 2001

SIM Space Interferometry Mission

A NASA Origins Mission

Summary

- Does SIM need global astrometry? ***YES***
  - Needed for SIM to explore the diversity of planetary systems
  - Needed to provide candidate solar-system analogs for TPF
- Does SIM do unique science? ***YES***
  - Planet search program will yield masses for a diversity of systems
  - SIM astrophysics program is compelling
  - SIM science goals cannot be achieved with other instruments or missions

SIM Space Interferometry Mission

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Why should SIM perform wide-angle astrometry ?

- Wide-angle is essential for identifying accelerations due to planets in long-period (> 5 AU) orbits
- Local reference frame must be 'tied' to global frame to suppress rotations/distortions
- Without this frame tie, the instrument capability is poorly utilized for long-period planets (~ 10x sensitivity reduction)
- Can frame tie be provided by other instruments? ***NO***
  - Hipparcos accuracy is inadequate
  - FAME grid would reduce this sensitivity loss to <~ 2x
  - This would strongly link SIM's primary science to another future mission

SIM Space Interferometry Mission

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Astrophysics with SIM

- The ability of SIM to perform astrophysics research is strongly endorsed by the astronomy community
- The 2001 NRC (McKee/Taylor) Report "*Astronomy and Astrophysics in the New Millennium*" reaffirmed the strong recommendation for SIM of the Bahcall Report:

> "A particular attraction of SIM is its ***dual capability:*** It enables both the detection of planets through narrow-angle astrometry and ***the mapping of the structure of our galaxy and nearby galaxies through wide-angle astrometry.*** It is critical that an accuracy of a few microarcseconds for wide-angle measurements be achieved in order to address a wide variety of fundamental problems throughout the decade."

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Astrophysics program was strongly endorsed by the SIMSWG

SIM Space Interferometry Mission

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- Stellar Astrophysics

  " SIM will revolutionize the traditional areas of stellar structure and stellar evolution."
- Galactic Structure

  "... SIM will determine distances accurate to 10% to objects that are twice the solar distance from the center ***on the opposite side of the Galaxy."***
- Cosmology

  "SIM will make fundamental measurements that will **directly impact** our understanding of **Cosmology."**

From the *Final Report of the SIMSWG* (D. Peterson, 2000)

What makes SIM unique for general astrophysics ?

SIM Space Interferometry Mission

A NASA Origins Mission

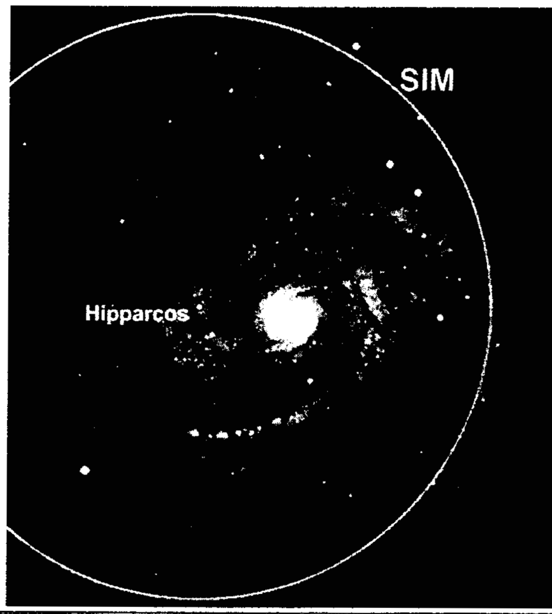
- The <u>combination</u> of two capabilities is not matched by any other instrument or mission:
  - Global astrometric precision to 4 microarcseconds
  - Faint targets down to 20th mag

Unique Science:
SIM's reach covers the entire Galaxy - and beyond

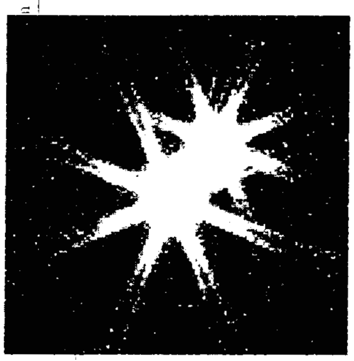
SIM Space Interferometry Mission

A NASA Origins Mission

- The combination of two capabilities is not matched by any other instrument or mission:
  - Global astrometric precision to 4 microarcseconds
  - Faint targets down to 20th mag



Unique Science: Stellar Evolution and the Distance Scale



A NASA Origins Mission

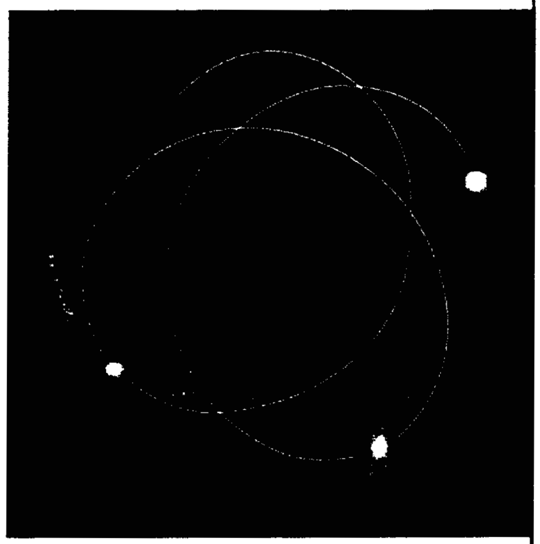
- Calibrate standard candles
  - Long-period Cepheids
  - RR Lyrae stars in field and globular clusters, spanning range of metallicities
- High-precision masses of stars (to 1 %)
  - M vs. L relation is poorly known for very high-mass and low-mass stars
  - Method: Astrometric binary orbits and parallaxes
- Stellar evolution: what are the maximum and minimum masses for stars?
  - Test stellar models including age and metallicity effects
  - Targets include:
    - OB stars, supergiants, red dwarfs, brown dwarfs, brown dwarfs

Unique Science: Dynamics of our Galaxy

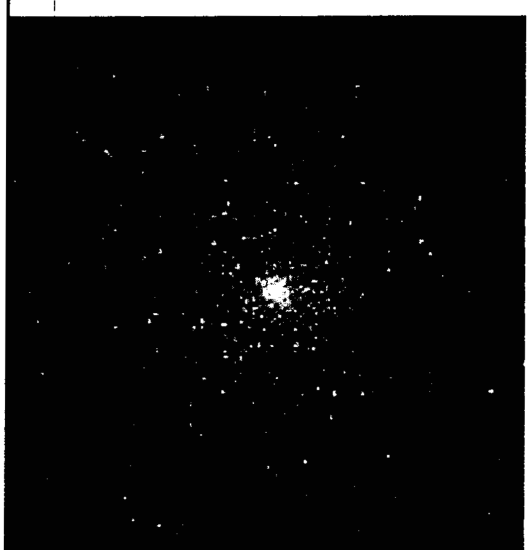
SIM Space Interferometry Mission

A NASA Origins Mission

- Study the 'classical' problems of size, mass distribution, and dynamics of
  - The Milky Way, using stellar velocities
  - The halo, via 'tidal tails' of dwarf spheroidals
    - Dynamically cold system
- Why SIM?
  - Provides proper motions: 2 of the phase-space parameters critical for constraining models
    - Proper motions to 0.1 km/s at 10 kpc
  - Need <u>both</u> astrometric accuracy and sensitivity

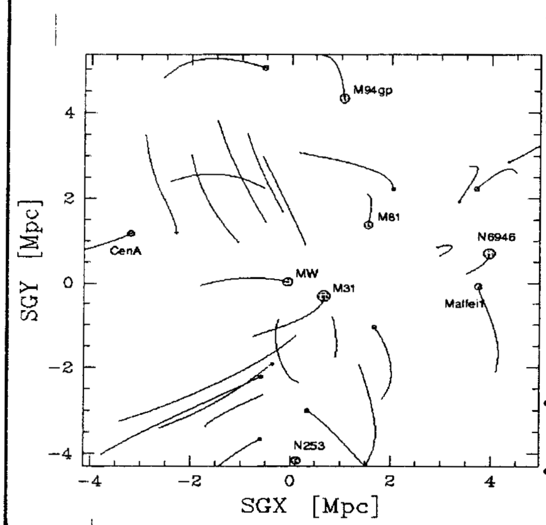


Unique Science: The Galactic Population II stars



- Study the role of Pop II stars in Galactic formation and evolution
  - Observe RR Lyrae stars in globular clusters and locally
    - Need accurate distances (luminosities) to globular clusters and halo field stars
    - Need metallicities spanning a wide range (~ -2.0 to -0.7)
  - Ages of globular clusters
  - RR Lyrae stars as distance indicators
    - Current luminosity uncertainty is as large as 0.3 mag
- Study steller populations in the bulge and halo with <u>astrometric microlensing</u>

Unique Science: Dynamics of Galaxies

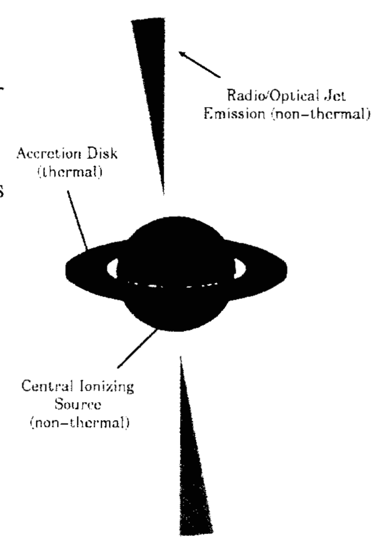


- Study galaxy dynamics, masses, orbital histories, etc.
  - using full orbit determinations
- Modeling of nearby galaxies (Local Group, M81 group, etc.) is ambiguous
  - Solutions based on radial velocities and photometrically estimated distances
  - SIM will provide proper motions (currently unmeasured)
- SIM will observe ~ 30 galaxies to ~50 μas/yr
- Requires SIM's faint-target capability (V = 16 ~ 20)

A NASA Origins Mission

Unique Science: Active Galaxies

- Astrometry as a tool for studying the unresolved nuclei of AGN
  - Requires both high accuracy and faint-target sensitivity
- Distinguish between jet and disk/corona as origin of non-thermal optical emission
  - Color-dependence of emission photocenter
- Study AGN spatial variability through astrometric shifts relative to local reference frame
- Astrometric stability of AGNs as fundamental optical reference frame 'tie points'



SIM Space Interferometry Mission

A NASA Origins Mission

Global astrometry: why SIM ?

- Astronomy typically advances most successfully through combination of survey and pointed observations
  - SIM and FAME are *complementary* missions
  - An analogy:
    - FAME is analogous to the Palomar Sky Survey
    - SIM is the 200-inch Hale Telescope of astrometry
- SIM will be 10-100 times more accurate than FAME, and will observe faint objects ($V > 15$) that FAME cannot observe at all
- FAME will provide targets for SIM
  - SIM can observe a list of up to $\sim 10^4$ objects observed at much lower precision by FAME
- SIM will observe 5 years before the launch of ESA's GAIA
  - SIM will 'skim the cream' of stellar and Galactic astrophysics

SIM Space Interferometry Mission
A NASA Origins Mission

Why we need SIM, even if we have FAME?

- FAME and SIM are complementary missions
  - FAME will observe a large number of stars, complete to $V \sim 15$,
    - Statistical studies, with >= 50 μas precision
  - SIM provides ultra-precise astrometry on faint objects ($V < 20$ mag)
    - Targets selected for scientific interest, at 4 μas precision
- Flexible (optimized) scheduling
  - SIM can be flexibly scheduled
    - Optimize planet-search sensitivity for a wide range of periods
    - Enable astrometry of microlensing events
    - Targets of Opportunity
  - FAME schedule fixed by the mission architecture
    - ~ 950 (~evenly-spaced) observations

SIM Space Interferometry Mission
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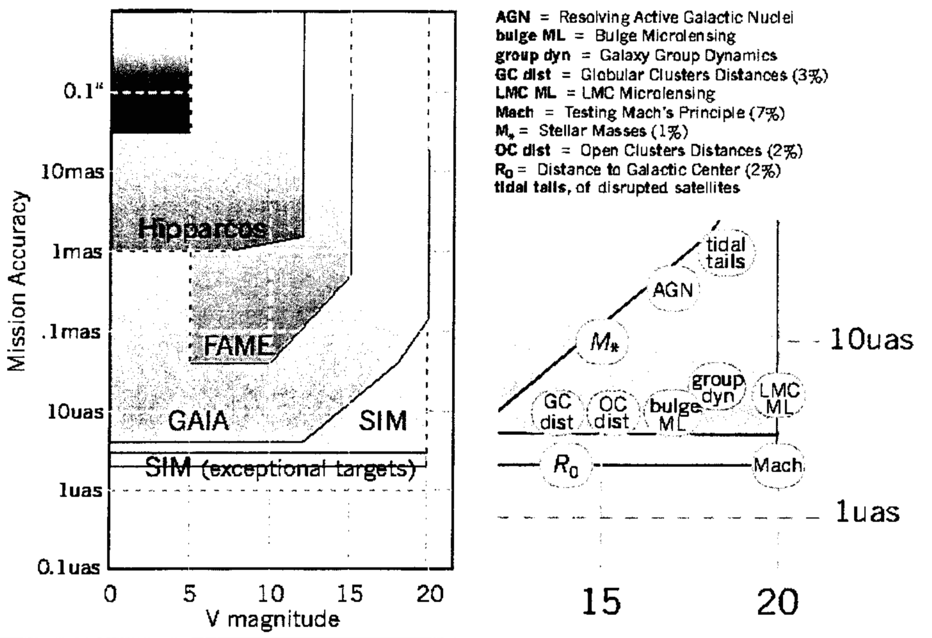
SIM global astrometry: high accuracy on faint targets



Planet searches: Other Missions

- Kepler Mission
  - Mature mission concept, but not yet approved (Discovery mission)
  - Statistics of prevalence of planetary systems: η_{Earth}
  - Will not identify specific targets for TPF
- FAME
  - MIDEX mission in Phase A
  - Statistics of brown dwarf (10 - 80 M_J) companions to solar-type stars
  - Fixed mission scheduling: up to ~2000 measurements
    - Mission accuracy (5 years) $\sigma_{mission}$ = 36 μas
- GAIA
  - ESA 'Cornerstone 6' mission
  - Fixed mission scheduling
    - Mission accuracy (5 years) $\sigma_{mission}$ = 4 μas
- SIM
  - Flexible scheduling: 2 x 50 measurements (log spacing)
    - Mission accuracy (5 years) $\sigma_{mission}$ = **0.15 μas**
      - in local reference frame

SIM Space Interferometry Mission

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Conclusions

SIM Space Interferometry Mission

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- Does SIM need global astrometry? ***YES***
  - Needed for SIM to explore the diversity of planetary systems
  - Needed to provide candidate solar-system analogs for TPF
- Does SIM do unique science? ***YES***
  - Planet search program will yield masses for a diversity of systems
  - SIM astrophysics program is compelling
  - SIM science goals cannot be achieved with other instruments or missions

Five Key Questions

SIM Space Interferometry Mission

A NASA Origins Mission

1. Does SIM fit in the larger framework of other missions and other techniques? ***YES***
   - SIM does unique science that no other planned mission can/will do
   - TPF needs SIM (technology, target identification, planet masses)
2. Is SIM feasible from an engineering and technology perspective? ***YES***
   - SIM new design is much less complex and risky than the Reference Design, and is now no more complex than missions that have successfully flown (per SIMTAC)
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap? ***YES***
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets? ***NO***
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry? ***YES***
   - This capability allows SIM to detect long-period (>5 year) planets necessary for TPF
   - Global Astrometry is a key science capability endorsed by the Decadal Reports

Space Interferometry Mission

SIM

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JPL

Wide Angle Astrometry with SIM - Stars

Todd J. Henry
Georgia State University

March 23, 2001

Overview

Space Interferometry Mission

SIM

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Precise Masses and Luminosities
- clusters
- exotic objects

Distance Scale
- globular clusters
- RR Lyrae luminosities
- Pop II and subgiants

Dynamics
- massive star formation in halo
- natal kicks of neutron stars

Why Measure Precise (1%) Masses?

SIM Space Interferometry Mission
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Individuals:

- challenge stellar astrophysics models
  - *location of true ZAMS*
  - *abundance effects*
  - *evolution within the main sequence*
  - *stellar lifetimes*
  - *mixing length, convective core overshoot*
- beginning and end of main sequence
  - *what is the largest star?*
  - *Boundary between stars and brown dwarfs*
- primaries for planet detection

Populations:

- mass-luminosity-age-metallicity relation
- mass function
- total mass in Galaxy

How to Measure Masses and Luminosities

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Masses — four parameters needed:

P *period*

a *relative semimajor axis*

π *distance via parallax*

f *fractional mass*

Luminosities — three parameters needed:

V *apparent brightness*

ΔV *fractional brightness*

π *distance via parallax*

SIM

Space Interferometry Mission

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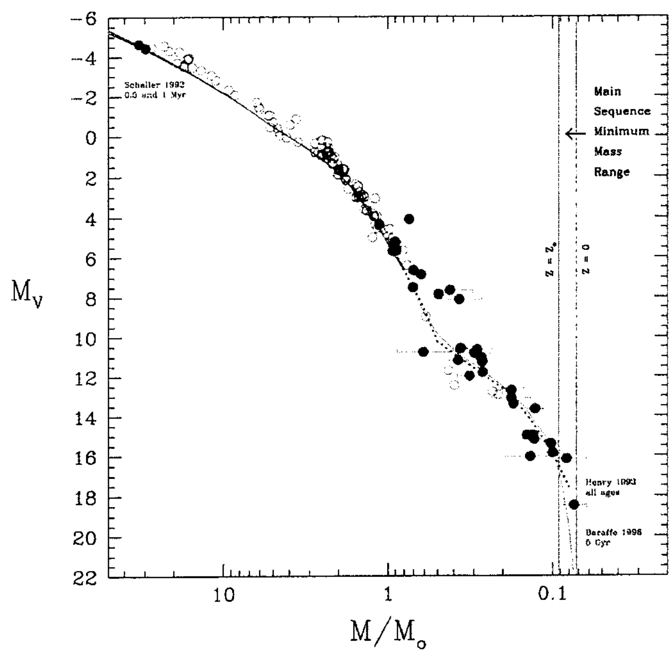

SIM

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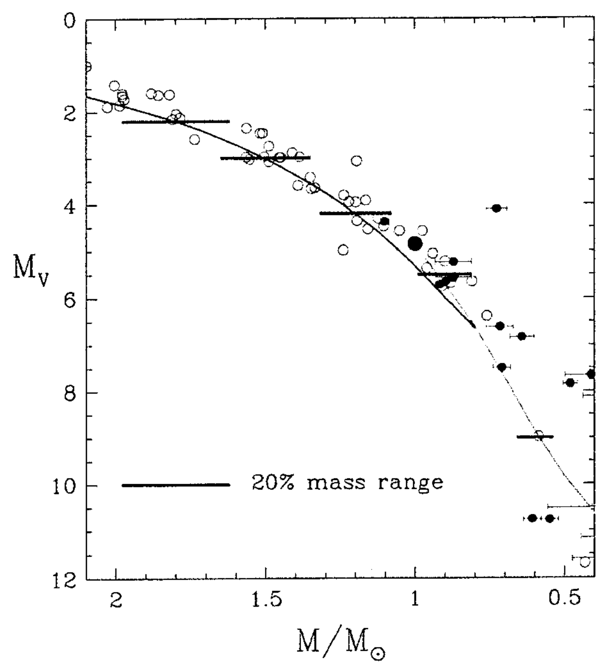

SIM Targets

Space Interferometry Mission
SIM
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Clusters

- Trapezium
- TW Hydrae
- Pleiades
- Hyades
- M67
- Globulars (21)

Exotics

- OB stars
- brown dwarfs
- white dwarfs
- neutron stars
- black holes
- AGB stars
- X-ray binaries
- radio binaries

State of the Art Masses for GL 748 AB

Space Interferometry Mission
SIM
A NASA Origins Mission

Masses — four parameters with HST:

P	2.4664 ± 0.0081	(0.3%)
a	0.1480 ± 0.0009	(0.6%)
π	0.0981 ± 0.0004	(0.4%)
f	0.3358 ± 0.0021	(0.6%)
M_A	0.3750 ± 0.0088	(2.4%)
M_B	0.1896 ± 0.0046	(2.4%)

The Need for SIM:

- this is a relatively easy system
- if P, a errors = 0 mass error still 1.3%
- if P, a errors = 0.1% and SIM determines π to 4 μas, f to 0.000014 (both 0.004%)

masses are known to 0.4%

SIM Space Interferometry Mission

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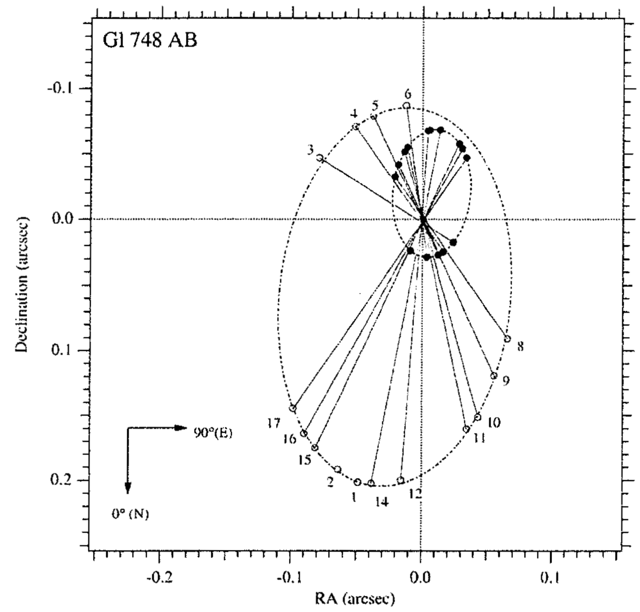

SIM Space Interferometry Mission

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SIM Advantages

1. SIM reaches faint magnitudes
- white, red and brown dwarfs
- distant open clusters (Trapezium, M67)
- globular clusters

2. SIM is incredibly precise
- distant objects (OB stars, supergiants, globulars)
- planet searches in binaries (solar neighborhood)

3. SIM solves lack of good radial velocities
- red and brown dwarfs
- OB stars
- black holes with massive companions

SIM Answers

Space Interferometry Mission

SIM

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What is the mass of the largest star?

What are the masses of black hole candidates?

What are the masses of very young stars?

What is the true dependence of the MLR on age?

Space Interferometry Mission

SIM

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Galactic Astrometry with SIM

Andrew Gould
Ohio State University

March 23, 2001

SIM Space Interferometry Mission

A NASA Origins Mission

Galactic Astrophysics - Key Project highlights

Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Microlensing

Andrew Gould
Ohio State University

Taking Measure of the Milky Way

Steven Majewski
University of Virginia

SIM Space Interferometry Mission

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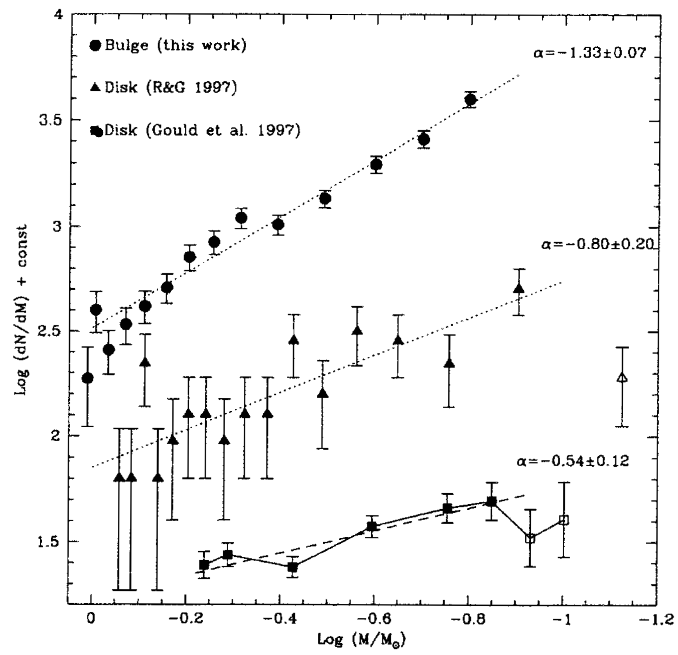

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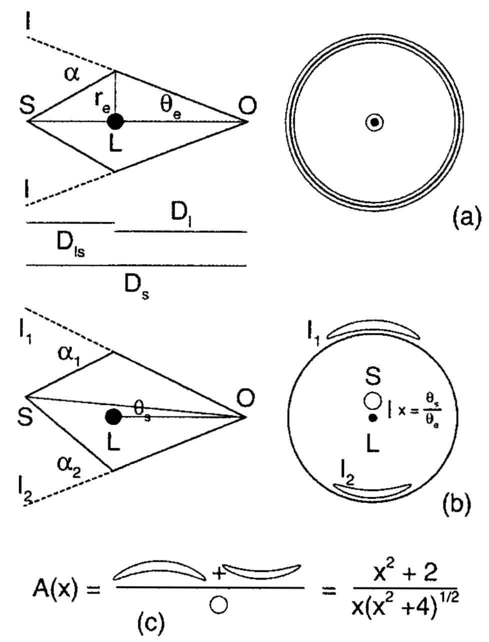

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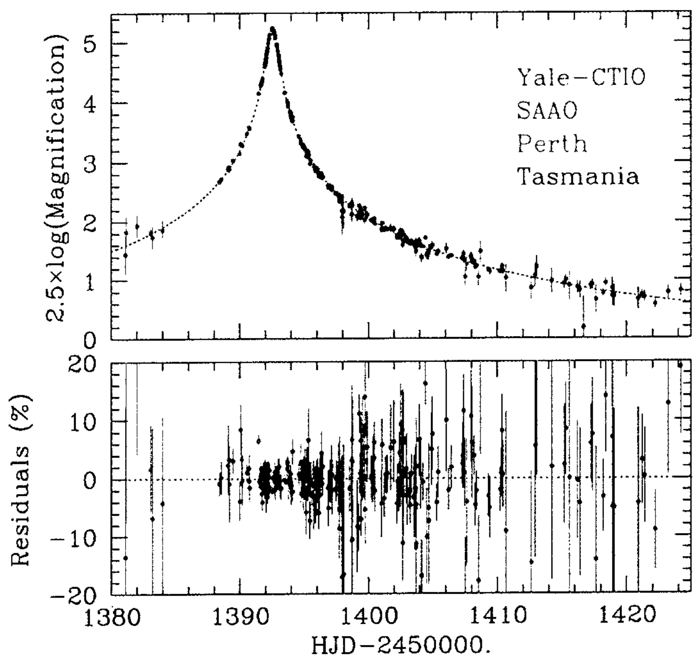

SIM Space Interferometry Mission

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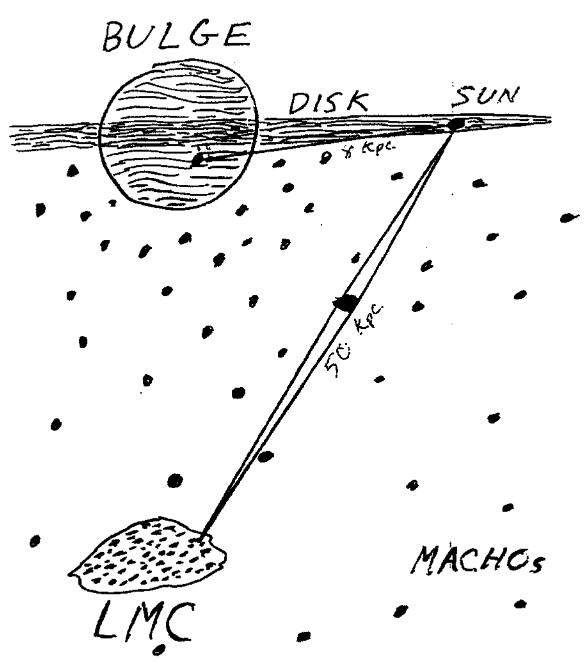

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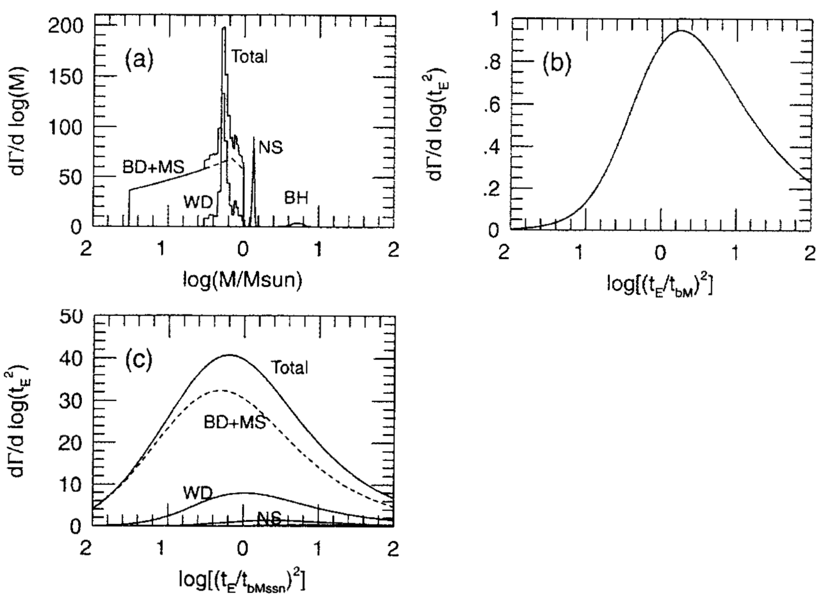

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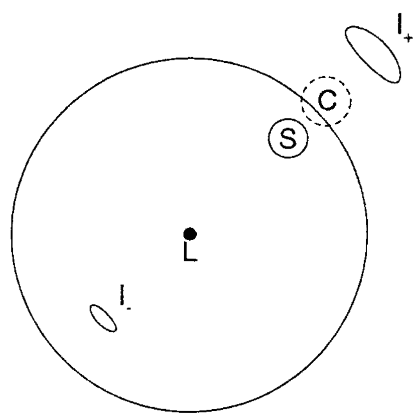

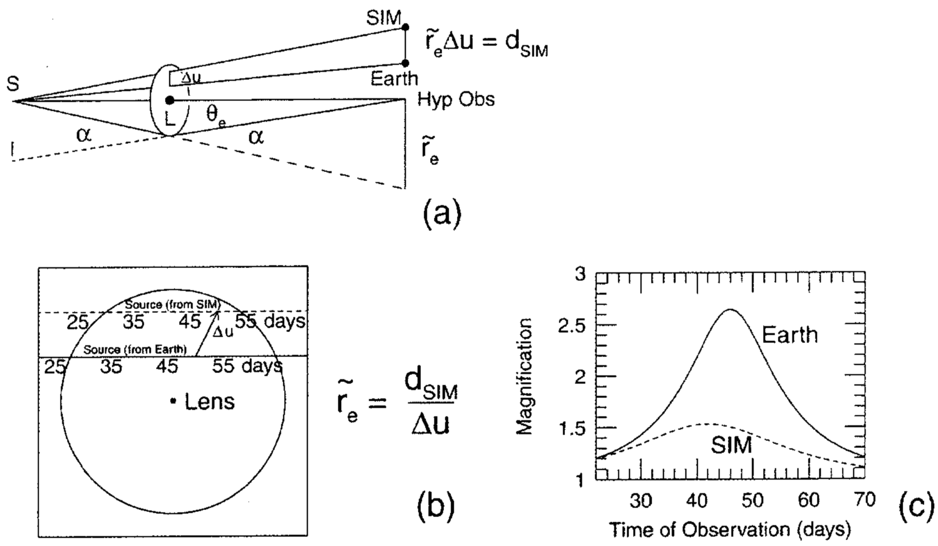

Space Interferometry Mission

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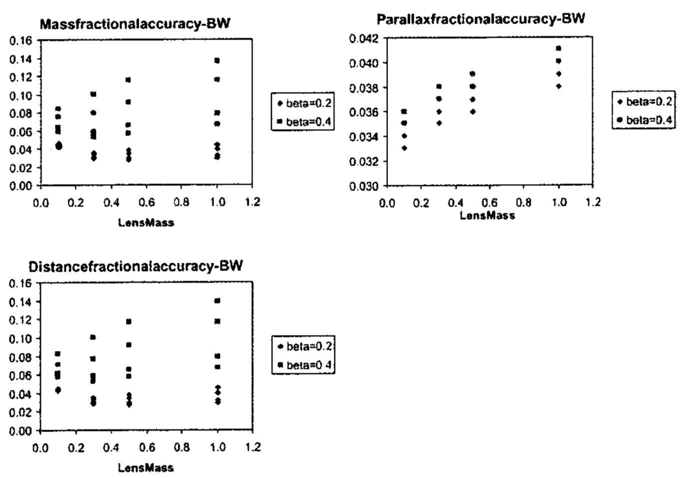
SIM

Microlensing experiment towards theGalactic bulge

t_{obs} =5hr

I_{source} =15



Taking Measure of the Milky Way

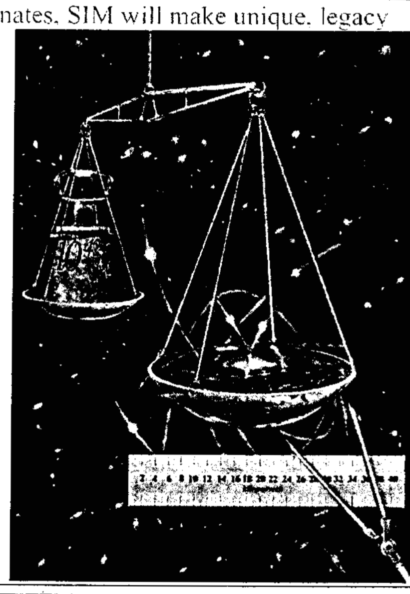
Space Interferometry Mission

SIM

A NASA Origins Mission

By completing 6-D phase space coordinates, SIM will make unique, legacy measurements of:

- Fundamental Galactic parameters, firmly establishing Galactic:
  - Mass scale → Total mass
  - Distance scale → Size
  - Dynamical scale → Rotation curve
- Stars in:
  - Galactic bulge
  - Disk to > $2R_o$
  - Halo to > 200 *kpc*
- Galactic stellar populations:
  - Field stars
  - Open and globular clusters
  - Satellite galaxies



The Milky Way as a Galaxy

Space Interferometry Mission

SIM

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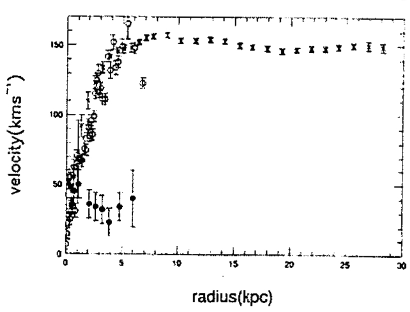
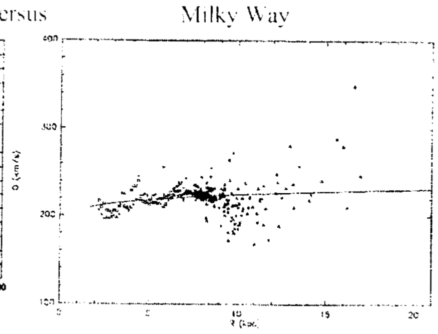
- Rotation curve of Milky Way is essentially unknown outside R_0

∴ Galaxy for which we have most detailed info cannot be placed on Tully-Fisher Relation

NGC 3198 versus Milky Way





Fundamental Galactic Parameters

Space Interferometry Mission

SIM

A NASA Origins Mission

R_o, Θ_{LSR}, important for virtually every problem in Galactic Astronomy

Fundamental for determining mass of Milky Way

Presently known to only ~20% (Θ_{LSR}) and ~15% (R_o)

Goal: 1% error in both R_o, Θ_{LSR} → 2% error in mass scale

Baade's Window

- With **wide angle capability**, SIM can:
  - Measure **absolute** π, μ for giants in Baade's window and around Sgr A*
  - Determine R_o, Θ_{LSR} to approaching 1% accuracy

Probe of Inner Galactic Potential

Space Interferometry Mission

SIM

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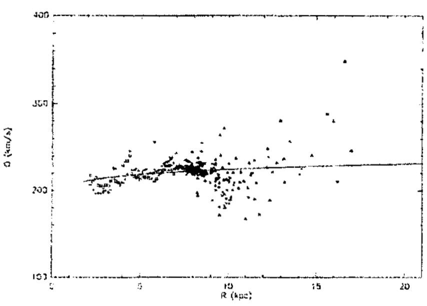
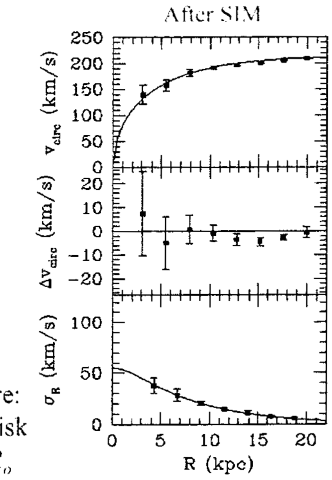
Before SIM



After SIM

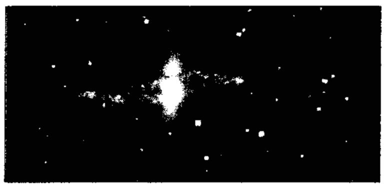


- Using appropriate tracers, SIM can measure:
  - Galactic rotation curve across entire disk
  - $V_{circ}(R)$ → disk potential to 2-3% ≤ $2R_o$
  - Local mass volume ($\rho_\odot$) and column ($\Sigma_\odot$) density
  - Amplitude, pattern speed, shape, wavelengths, phase for large non-axisymmetries (bars, warps, spiral arms)

Mass of Galaxy to Large Radii (Dark Halo)

- SIM is only means for obtaining precision μ's in outer Galaxy
- SIM can determine Mass(R) to $R > 200$ *kpc* via complementary methods:
  - Jeans Equation:
    ~1000 random field giants, Galactic globulars and satellite galaxies
  - Stars in tidal streams (e.g., Sagittarius):
    ⇒ Milky Way potential from backwards integration of debris orbits

Polar ring galaxies:
proven gravitational laboratories



Simulation: Formation of tidal tails

SIM Space Interferometry Mission

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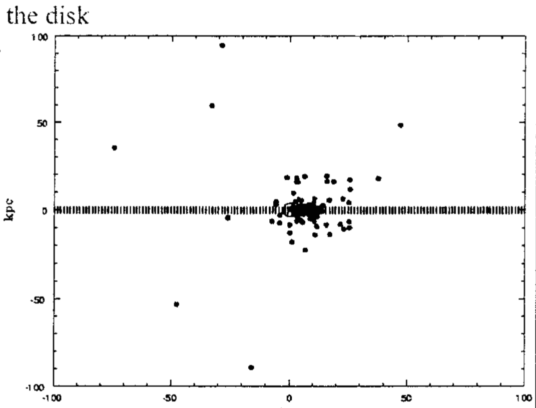
Fundamental Contributions to Stellar Population Studies

- Orbits for every Galactic satellite galaxy
- Orbits for ~ every Galactic globular cluster
- Orbits for hundreds of Galactic open clusters
- Velocity ellipsoid variations in disk/halo
- Age-velocity relations in the disk
- Studies of the central bar
- Dynamics of bulge stars



Distribution of Galactic globular clusters in x-z plane

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Space Interferometry Mission

External Review Board

Wide Angle Science: Extragalactic

Ann E. Wehrle
Key Project Principal Investigator

March 22 & 23, 2001

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Extragalactic Key Projects

- Binary Black Holes, Accretion Disks, and Relativistic Jets: Photocenters of Nearby AGN and Quasars
  - Ann Wehrle (PI, ISC/JPL/Caltech), Dayton Jones, Steve Unwin, Dave Meier (JPL), Glenn Piner (Whittier College)
- The Astrophysics of Reference Frame Tie Objects
  - Kenneth Johnston (PI), Ralph A. Gaume, Norbert Zacharias, David Boboltz, Alan Lee Fey (USNO)
- Dynamics of Galaxies
  - Ed Shaya (PI, Raytheon ITSS), Jim Peebles (Princeton), Brent Tully, John Tonry (IfA/Hawaii), Kirk Borne (Raytheon ITSS), Dennis Zaritsky (Lick Obs./UCSC), Stuart Vogel (U of MD), Adi Nusser (Technion Inst. Of Israel)

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Black Holes at the Centers of Galaxies

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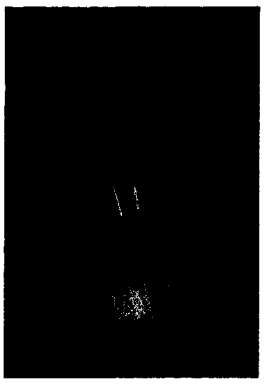
- **Black holes of 10^9 solar masses merge when two galaxies collide; Timescale about a million years.**
- **Accretion fuels the jets. Quasar "core" is the ensemble of emission from the jets, accretion disk, and clouds of ionized gas.**



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The Nature of Active Galactic Nuclei

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Questions 1 and 2 - jet and black hole physics

1. Do the cores of galaxies harbor ***binary*** supermassive black holes remaining from galaxy mergers?
2. Does the most compact optical emission from an AGN come from an ***accretion disk*** or from a ***relativistic jet***?

Question 3- tying the SIM reference frame to the ICRF

3. Does the separation of the radio core and optical photocenter of the quasars used for the reference frame tie change on the timescales of their photometric variability, or ***is the separation stable***?

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Astrometric Signature

JPL

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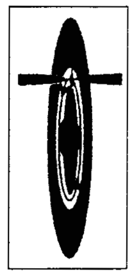
- **Binary black holes can be detected by astrometric reflex motion of their photocenter, just like we detect planets around stars.**
- **Scales: Projected separation of candidate binary black hole in quasar OJ287 is 11 microarcseconds; period 24 years, motion in 5 years is 14 microarcseconds. Other active galaxies like M87 are closer and motion is easier to detect.**



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Does the compact emission come from jets or disk?

JPL

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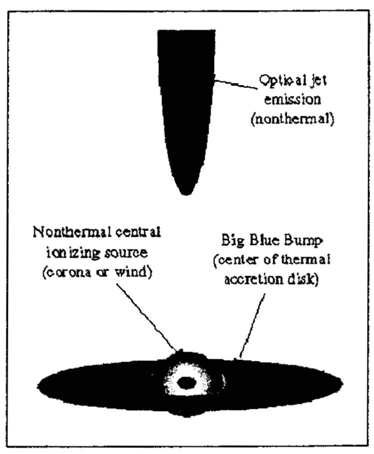
- **Accretion disk radiates thermal emission with peak in near-UV. Size: 0.012 parsecs, (=2 lightweeks), at distance of M87 about 160 microarcseconds in diameter (brighter in blue than in red part of spectrum)**
- **Corona or wind radiates non-thermal emission (Brighter in red than in blue).** ***Both red and blue photocenters centered on BH***
- **Relativistic jets also radiate non-thermal emission. Base of the jets is offset from the core by some hundreds of times the diameter of the accretion disk (brighter in red than in blue).** ***Red photocenter offset from blue photocenter in direction of the jets.***
- ***Technique: measure phase shift of white light fringe between red and blue halves of SIM detector.***



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Reference Frame Tie

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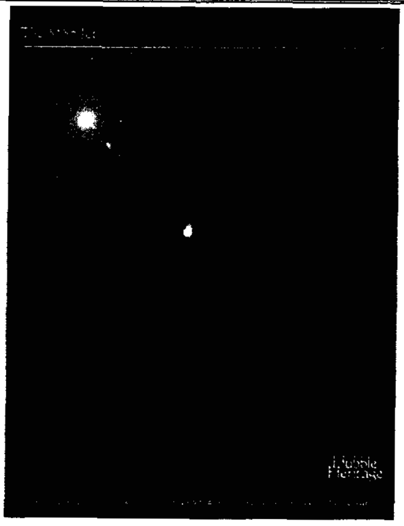
SIM Space Interferometry Mission

- ICRF defines the positions of celestial objects relative to radio-bright quasars, IAU standard of reference
- SIM reference frame needs to be tied to the ICRF via objects in common- bright quasars with compact radio structure on mas scales.
- But we need to know if the separation of the radio and optical cores is ***stable or variable*** on timescales of weeks to years.



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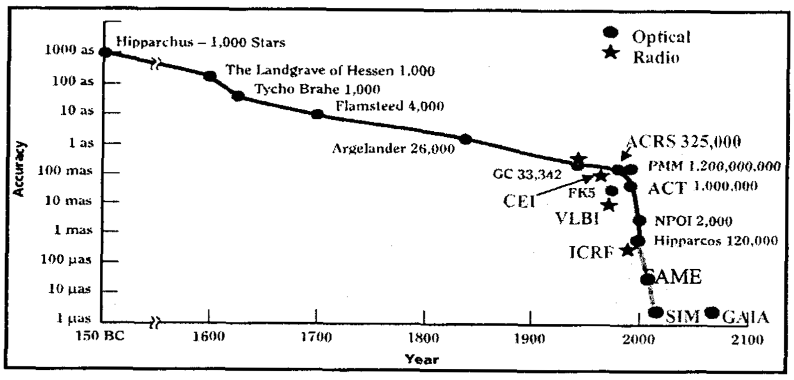
Optical Structure Makes M87 Unsuitable?

FAME - SIM Synergy

JPL

SIM Space Interferometry Mission

- **SIM Calibration from FAME**
  - **Reduce overhead**
  - **Identify problem stars**
- **Grid Comparison**
  - **Different construction methods**
  - **Zonal distortions**



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Extragalactic Frame Tie

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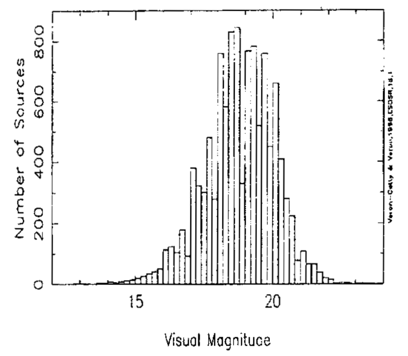
SIM Space Interferometry Mission

- ICRF Frame Tie
  - Currently limited to about 100 μas
- FAME
  - Sensitivity V~15th
  - Accessible Quasars ~ 60
- SIM
  - Sensitivity V~20th
  - Accessible Quasars ~9000
- Frame Rotation
  - *SIM more stable than FAME*
  - *SIM can remove FAME frame rotation*

Quasar Visual Magnitude Distribution



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SIM Dynamics of Galaxies: Project Goals

JPL

SIM Space Interferometry Mission

- Derive parameters of fundamental importance to cosmology and the origin of structures:
  - orbital histories, galaxy total masses, dark matter fraction, group total masses, age of the Universe.
- Place constraints on the statistics of mergers and on angular momentum histories
- Total masses and dark matter distribution can be determined for the 1-5 Mpc scales.
- Dynamical friction and merger history become evident as deviations from standard solutions.

A NASA Origins Mission

SIM Dynamics of Galaxies: Project Method

- Measure proper motions for ~30 nearby galaxies with precision of 10-40 km/s.
  - Local Group and nearest galaxy groups.
  - Use 3-10 brightest stars in each galaxy.
- Use SIM standard candle calibrations and velocity parallaxes to complete our knowledge of accurate 3-d velocity and 3-d positions.
- Apply these measurements as boundary conditions in gravitational models of orbital dynamics.

SIM Space Interferometry Mission

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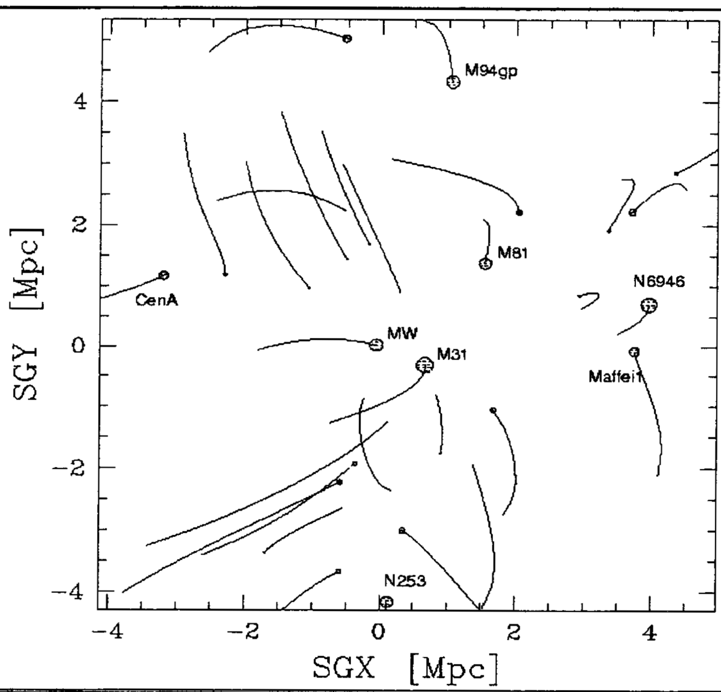

SIM Space Interferometry Mission

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SIM and the d < 5 Mpc region

SIM Space Interferometry Mission — A NASA Origins Mission

- Improved Distances
  - Current methods can get distances to ~5%.
  - In 10 years, *with SIM*, we expect ~2% accuracy
- Improved Masses and Orbits- Constraints
  - Cosmological constraints (confirmed by MWB experiments) imply the initial peculiar velocities were very small.
  - Ground-based measurements give accurate RA, DEC, radial velocity.
  - Ground-based distance measurements made accurate by SIM calibration
  - SIM measurements of pm(RA), pm(DEC)
- Improved Masses and Orbits - Modelling
  - Solve for galaxy orbits and internal mass distribution with average of three-ten stars per galaxy to obtain motions of galaxies
  - With 25 galaxies, solve N-body problem with constraints at early-Universe and current-day times.
  - Highly overconstrained problem is soluble as a set of differential equations with mixed boundary conditions (use Numerical Action Method of Jim Peebles, 1989)

Summary

SIM Space Interferometry Mission — A NASA Origins Mission

- AGN
  - Distinguish between jet and disk/corona as origin of non-thermal optical emission.
  - Establish level of astrometric stability of AGNs as fundamental optical reference frame "tie points"
  - Explore movements of optical structures by measuring astrometric shifts relative to local reference frame of "stable" AGN
- Dynamics of Galaxies
  - Dark matter dominates the mass of the universe but extremely little is known of how much there is or how it is distributed. It appears to be clumped at the 5 Mpc scale or less.
  - Provide basic observational data on motions of galaxies within 5 Mpc.
  - This is the volume that SIM can survey well, and can map out through the detailed motions of many galaxies
- **SIM is the only foreseeable mission that can do these measurements.**

Backup Slides

SIM Space Interferometry Mission

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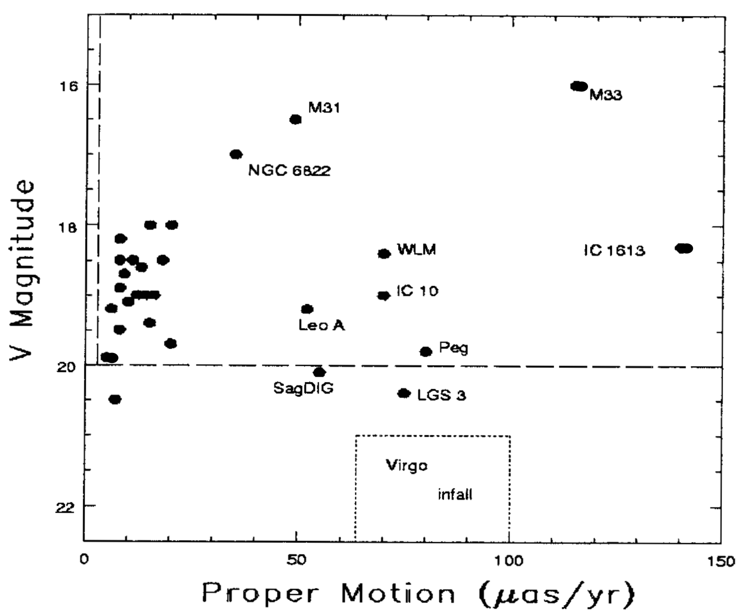
SIM Space Interferometry Mission



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Complex Issues

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- **Trajectories may pass through neighbors' halos**
- **Some dark matter may not reside in galaxies.**
  - **Hence, dynamical friction may result.**
- **Late time, long range mergers are a problem.**
  - **short range mergers do not present a problem.**
- **Possibility of dark matter objects.**
  - **e.g., a present day pre-collapse overdensity.**

SIM Space Interferometry Mission

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SIM Space Interferometry Mission

An Optical Nucleus and Jet at 0.1 arcsecond resolution

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Color Dependent Differential Astrometry

- SIM has 80 spectral channels
- Phase shift *between* spectral channels unaffected by value of group delay or its uncertainty- hence, much more powerful than group delay.
- Simple experiment: divide 80 channels into "red" and "blue" groups, average over group, find offset from difference in averaged phases.
- Astrometric accuracy reduced by only 2*SQRT2 due to half the photon count and doubling length of white light fringe envelope.
- Easy to detect shift of 15 microarcseconds in a single measurement.
- Shift of 30-100 microarcseconds are expected for quasar targets such as 3C345

SIM Space Interferometry Mission

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SIM Space Interferometry Mission

Summary of Science Possible With Re-scoped SIM

C. Beichman for the SIM-SWG

March 4, 2001

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Planet Finding With Rescoped SIM

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SIM Space Interferometry Mission

- Preserves all of the narrow angle capabilities of previous versions for SIM
- Advances our astrophysical understanding of formation and evolution of planets
  - Survey ~2,000 stars to levels of Uranus masses (15 Earth masses) over a wide range of stellar properties (age, metallicity, spectral type) and orbital locations
  - Study formation, migration and evolution of planets from 1 Myr to 1 Gyr
- Achieves primary Origins requirement of characterizing the solar systems that may exist around the closest 250 stars in support of the Terrestrial Planet Finder (TPF)
  - Find and measure masses of planets down to a few (3-10) Earth masses which is within the range expected for rocky planets

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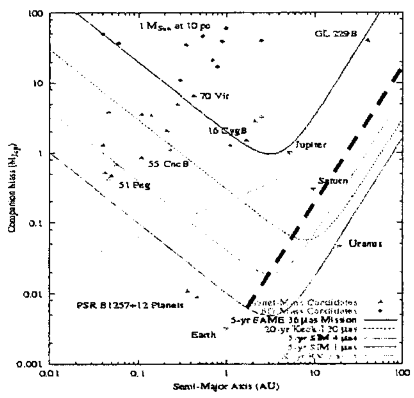
Planet Finding *Needs* Wide Angle

Space Interferometry Mission

SIM

- Wide angle astrometry is necessary to identify the small accelerations due to planets on long period orbits (> 5 AU)
  - We need to identify Solar System analogs (Uranus in >Jupiter orbits)
- Rotation and other distortions of the grid of local reference stars will introduce astrometric errors comparable to or greater than expected signals of 1-3 μas
- FAME/GAIA reference stars could reduce effect, but imposes strong dependence on the success of these missions



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Rescoped SIM Preserves General Astrophysics Goals

Space Interferometry Mission

SIM

- Two NAS decadal reviews have endorsed the fundamental astrophysics enabled by wide-angle astrometry
  - Only SIM can observe objects as faint as 20 mag with astrometric accuracy of 4 μas
  - SIM-SBL maintains these capabilities except for astrometry in crowded fields
- Astronomy typically advances most successfully with a combination of pointed and survey observations
  - Detailed pointed observations of 10^4 objects of particular interest with SIM will complement the astrometric survey planned with the FAME mission

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SIM Extends General Astrometry Far Beyond FAME and Hipparcos

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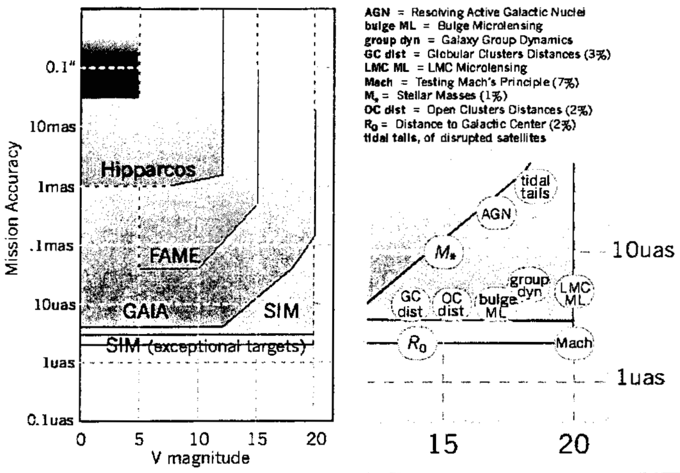
- SIM observe faint objects that FAME cannot observe at all (V>15 mag)
- SIM will come at least 5 years before launch of GAIA



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General Astrophysics with SIM

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SIM Space Interferometry Mission

- Calibrate Cepheids and RR Lyrae stars as a distance indicators, taking metallicity into account
- Measure masses with 1% accuracy over the whole range of stellar types and ages
- Investigate the dynamics of the Milky Way
- Study galaxy dynamics based on true orbit determinations
- Use astrometry at different colors to distinguish between various jet and disk models of AGN
- Determine physical properties of micro-lensing systems
- Test Mach's Principle to 5% accuracy

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A Lean, Mean Astrometry Machine

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SIM Space Interferometry Mission

- The preceding topics are just a sampling of what SIM will able to accomplish in 5 year mission
  - Over the next 5 years, astronomers will develop new projects to use the remaining ~50% of observing time on SIM
  - FAME will result in exciting projects requiring SIM follow-up
- While the rescoped SIM is dramatically simpler than earlier designs, it has given up relatively little astrometric performance
  - Astrometry in regions with extended emission is compromised by loss of uv-plane coverage
  - Modest efficiency loss compared with SIM-Classic
  - Visible light imaging in line and continuum, TPF nulling test on 10 m scale has been lost

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What Does TPF Need to Know?

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SIM Space Interferometry Mission

- Frequency of Planets
  - Aperture needed for TPF telescopes scales as distance.
    - If Earth's are common, then nearest stars may contain Earth's and a version of TPF with 1-2 m apertures may be adequate.
    - If Earth's are rare, then TPF may have to search and measure Earths as far away as 15-25 pc with 3-5 m telescopes.
  - Kepler and SIM Broad Survey will determine frequency of Earths around relevant stars
    - Micro-lensing studies (M,L,T) stars 4 kpc away of unknown metallicity
- Specifics of Nearby Stars
  - SIM Deep Survey will identify good (and bad) candidate systems for TPF targets down to few Earth masses, allowing TPF to focus early on spectroscopy
    - ECLIPSE will provide information on Jupiters in >3 AU orbits
  - SIM will validate early TPF results and provide additional information critical for interpretation of photometric/spectroscopic data
    - What is the mass (or upper limit) to a target detected by TPF?

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The Road to TPF and Beyond

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SIM Space Interferometry Mission

- Following a disciplined technology program leading to the required picometer performance, SIM can accomplish its scientific goals by early in the next decade
  - Find targets for TPF and advance our understanding of the formation and evolution of planetary systems
  - Carry out the astrophysics science program endorsed by Bahcall and McKee/Taylor
- SIM will also develop interferometry and associated technologies as a viable techniques for future astrophysics missions
  - *Nanometer* technology for TPF and for long term interests in optical to sub-mm interferometry
  - *Picometer* technology for X-ray interferometry

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SIM Is Not Necessarily on the Optimum Path to TPF

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SIM Space Interferometry Mission

- Optimum paths do not necessarily exist
- None of the planet-finding alternatives to SIM are easy and none have been as studied as deeply as SIM
  - SIM has the benefit of $100M worth of study, technology development, and engineering detail.
  - Other, superficially more attractive missions have only been studied at the level of a few $100k to a few $1M (FAME, TPF, TPF-Lite, GAIA, NGST).
  - We don't know how to do any of these other missions
- Apart from a few well defined technology gaps (picometer!) that are addressed by technology program and testbeds, the newly simplified SIM is ready to go within the $930M cost cap.

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SIM Space Interferometry Mission

Choose Your Slogan

- "*When the going gets tough, the tough go shopping*" --- for a new mission
  - If we give up on projects when the going gets tough, we will never bring Origins technologies to maturity
- Yes, but..."*You have to know when to hold them and know when to fold them*"
  - Origins Subcommittee has recommended technology milestones for SIM (MAM-1 and MAM 2~3) that SIM must meet on a strict timetable over the next two years before entering development...or face cancellation.

If interferometry in general and Origins science in particular is ever to become more than a viewgraph exercise, we have to weigh seriously the consequences of quitting now

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Space Interferometry Mission

SIM

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External Review Board
Project Summary

Tom Fraschetti

SIM Project Manager

23 March 2001

JPL

Selecting Shared Baseline

Space Interferometry Mission

SIM

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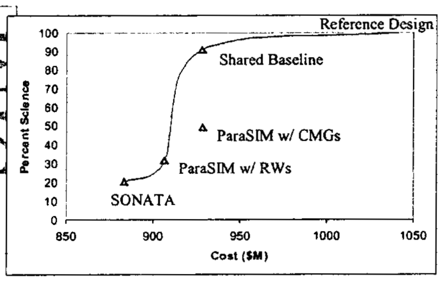
Science Performance Summary		Number of targets and time percentage for a 5 year SIM mission							
Observing Program	Accuracy	Shared Baseline	%	ParaSIM	%	ParaSIM with CMG's **	%	SONATA	%
Deep Search	1 uas	250	17.5	250	41.2	250	22.5	250	24.1
Broad Survey	4 uas	2000	9.5	540	28.8	1570	47.5	1900	45.9
Wide Angle: Bright or Faint	10 uas	31800 or 4390	43.0	0+	0.0	0+	0.0	*****	



- Sonata will will not detect long period planets
- ParaSIM with reaction wheels throughput does not meet requirements for finding Planets
- ParaSIM with CMG's costs as much as Shared Baseline

Five Key Questions

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SIM Space Interferometry Mission

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1. Does SIM fit in the larger framework of other missions and other techniques? ***YES***
   - SIM does unique science that no other planned mission can/will do
   - TPF needs SIM (technology, target identification, planet masses)
2. Is SIM feasible from an engineering and technology perspective? ***YES***
   - SIM new design is much less complex and risky than the Reference Design, and is now no more complex than missions that have successfully flown (per the SIMTAC)
   - SIM's key technologies will be demonstrated before we enter Phase B
3. Can SIM be built at the proposed cost cap? ***YES***
   - The Independent Cost estimate agrees with the Project estimate within 10%, and we are carrying an unencumbered 40% Phase C/D cost reserve and 6 months of costed Phase C/D schedule reserve
4. Can the cost of SIM be significantly reduced if we restrict the science to only extra-solar planets? ***NO***
   - No other known architecture offers a lower cost than SIM
   - We have found the optimum science vs cost design option for SIM
5. Does SIM need global astrometry? ***YES***
   - This capability allows SIM to detect long-period (>5 year) planets necessary for TPF
   - Global Astrometry is a key science capability endorsed by the Decadal Reports